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ELECTROMYOGRAPHICAL AND CINEMATOGRAPHICAL ANALYSIS OF WALKING BACKWARDS

by

© JOHN FRANK KRAMER

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "Electromyographical and Cinematographical Analysis of Walking Backwards" submitted by John Frank Kramer in partial fulfilment of the requirements for the degree Doctor of Philosophy.

Date. October ....

ABSTRACT

Backward movement is an aspect of daily life for most individuals and it is a crucial element in most sporting activities. Backward walking is a basic component of backward movement. In direct contrast to forward walking, backward walking has received only minimal attention in the published literature. The present investigation was undertaken to provide basic information describing the backward walking cycle in man.

Two 16 mm film records were synchronized by means of an impulse generator which simultaneously activated internal timing lights within each camera. Camera One photographed the subject's lateral aspect, while Camera Two, equipped with a split lens, photographed the subject's anterior aspect and the four simultaneous oscilloscope electromyograms. The subject alternated backward and forward walking trials until a total of nine walking trials had been completed in each direction. The position of the four pairs of surface electrodes was changed after three walking trials in each direction, such that a total of twelve left lower extremity muscles were examined during each gait.

The backward walking cycle was first divided into specific events, phases and sub-phases which corresponded to the divisions of the forward walking cycle. The principle of moments was utilized to calculate the position of the body center of mass and the cosine law was utilized to calculate joint angles of the left hip, knee and ankle in selected frames of Film One. The position of the lateralmost point on the left hip was determined from corresponding frames of Film Two.

The following are the major results of the study: (1) the backward and the forward walking cycles were each divided into three stance phase sub-phases and two swing phase sub-phases on the basis of five specific events, (2) normal backward walking was slower than normal forward walking in terms of cadence and horizontal velocity, (3) backward stride and step lengths were shorter than forward stride and step lengths, (4) within each gait the vertical displacements of the top of the head and the calculated body center of mass were similar, (5) peak-to-peak vertical displacements of the body center of mass were significantly greater during backward walking than during forward walking, (6) the vertical high points of the body center of mass during both gaits occurred shortly after malleoli-even of mid-stance of alternate legs, (7) the vertical low points during backward walking occurred near the end of the double limb support periods, while during forward walking the vertical low points occurred at the start of double limb support periods, (8) lateral and peak-to-peak lateral-medial displacements of the lateralmost point on the left hip during backward walking were similar to the corresponding forward walking displacements. However, medial displacements during backward walking were significantly greater than medial displacements during forward walking, (9) changes in the horizontal velocity of the body center of mass, calculated over 5% divisions of the walking cycles, were small and inconsistent during both gaits. Overall, there was a tendency for horizontal velocity to decrease slightly as the body ascended to its vertical high points and then to increase slightly as the body descended toward its vertical low points. However, within each gait the mean ascending horizontal velocity did not differ significantly from the mean descending horizontal velocity, (10) the joint excursions of the

left lower extremity during backward stance and swing phases were approximate reversals of the joint excursions observed during the corresponding forward walking phase, (11) the total joint range of motion observed at the hip and the knee was slightly greater during forward walking, (13) ankle joint excursion was similar during both gaits. However, during backward walking this range was achieved through increased dorsiflexion and decreased plantarflexion as compared to forward walking, (14) the muscles of the left lower extremity were electrically active for longer periods of time during backward walking and also demonstrated a greater degree of inconsistent electrical activity during backward walking.

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CHAPTER ONE

STATEMENT OF THE PROBLEM

I. INTRODUCTION

Forward walking in man has been the subject of considerable discussion. The physical act of walking has been broken down into phases and sub-phases, and analysed in terms of temporal, spatial (2,3,19,28,30,31,32,33,34,38,50,54,55,59,62,63,67,68,69,70,71,75,76, 77,78,81,85,86,87,93,103,106,107,108) and muscular coordination (3,4, 8,9,11,12,13,14,15,21,27,29,30,31,32,42,43,44,49,51,59,63,77,91,92,94, 99) parameters.

Medically oriented researchers have felt that by establishing standards of normal variability as a basis for comparison, physicians and therapists could more readily and appropriately advise handicapped individuals. Medically, knowledge of what is normal is considered necessary to understand the causes and effects of abnormalities.

Physical educators, on the other hand, have felt that by understanding the parameters that characterize top level performances they could better provide coaches and athletes with the basic bio-mechanical and physiological principles on which to base the pursuit of optimal performance.

Despite the interest in forward walking, published research concerning backward walking has been minimal. Utilized to a lesser extent than is forward walking and over much shorter distances walking backwards is, never-the-less, an important, although often ignored, activity in the daily life of most individuals. Walking and running backwards are integral aspects of most sporting

activities. Still, therapists and, particularly, coaches have failed to consider the significance of backward movement. The inability to walk safely backwards is a security hazard for both normal and handicapped individuals. In sport, defensive play is frequently characterized by the necessity to move rapidly and agilely backwards. Often, backward locomotion is a key determinant in team and/or individual success.

In both daily life and in sport the physical activity of walking is often complicated by the necessity to simultaneously perform other skilled activities including balancing or manipulating objects such as tools and athletic equipment. Simultaneously avoiding or encouraging collision with other objects such as terrain, furniture and opponent players can further complicate movement. When coupled with yet additional variables such as changing direction, acceleration and displacement, purposeful movement becomes increasingly complex.

Backward movement often serves to place the individual in a more advantageous position to carry out the task at hand, whether sitting down in a chair or maintaining defensive position in basketball, or to facilitate carrying out another task such as raking, sweeping, shoveling or achieving an unguarded position in sports competition.

Medically, important diagnostic conclusions are often drawn from the way a person walks (9). In the medical specialities of neurology, rheumatology, physical medicine and orthopedics it is customary to observe the patient's gait for clues to pathological conditions. The patient who lacks the ability to move backwards safely is in a dangerous position because backward movement is a

necessary aspect of many daily activities.

In sports, backward movement is a crucial aspect of most sporting activities. Athletes and/or coaches who do not develop this skill risk never realizing full athletic potential in that activity.

The basic parameters that characterize backward walking in man have not been extensively investigated. That which is normal or abnormal, efficient or inefficient is undefined. The present investigation focused on backward walking as the basic unit in backward movement. By describing this basic pattern it is hoped that a greater understanding of and appreciation for backward movement, both in daily life and in sport, will be forthcoming.

II. THE PROBLEM

The purpose of the present investigation was to provide a basic description of backward walking in man, focusing on the following:

1. The division of the backward walking cycle into component phases and sub-phases which are of functional significance and which can be related to the forward walking cycle.

2. The temporal and spatial relationships of the component phases and sub-phases, and their significance in backward walking.

3. The electromyographical description of the muscular pattern characteristic of walking backwards and the inter-relationships of this pattern with the temporal and spatial sequence of activity.

III. DELIMITATIONS

1. Walking backwards was restricted to the technique in which the subject faced in one direction and walked in the opposite direction. The path of movement was along the subject's YZ, or

sagital plane. The XY, or frontal plane of the body remained essentially at right angles to the path of movement.

2. Description was restricted to the performance of one male subject walking backward and forward over a level, horizontal indoor surface.

3. Electromyographic description was restricted to examination of twelve muscles of the left lower extremity; the muscles being examined four at a time on the four channel electromyograph.

4. Description was restricted to examination of single walking cycles at a speed selected by the subject to be a normal or free speed.

5. Description was restricted to selected frames of film corresponding to 5% intervals of the walking cycles.

IV. LIMITATIONS

1. The accuracy of determining the body center of mass and the lower extremity joint angles was limited to the accuracy of the Humanscale anatomical data (26) and to the ability of the examiner to locate joint centers on the subject.

2. The accuracy of determining the muscular pattern of activity was dependent upon the examiner's ability to locate particular muscles and to record and access accurately the electromyograms from these muscles.

3. The accuracy of determining the temporal and spatial sequence of activity was dependent upon the ability of the examiner to distinguish accurately the various degrees of foot-surface contact.

CHAPTER TWO

REVIEW OF THE LITERATURE

I. INTRODUCTION

Considerable research effort has centered on forward walking and the means by which data suitable for detailed biomechanical study could be gathered and analysed. However, backward walking has received only minimal attention to date in the published literature.

Many of the research methodologies and biomechanical principles developed and discussed with reference to forward walking relate to backward walking as well. A thorough understanding of both the experimental methodologies and the forward walking cycle itself are necessary to permit a more logical approach to the study of backward walking.

II. BIOTELEMENTRY

The confined laboratory situation cannot duplicate precisely the emotional or energy demands existing in physical activities. The time required to fit and align various scientific instruments attached to the subject, as well as their physical interference with normal movement patterns, may impose additional stresses upon individuals, or modify those stresses normally present.

The term biotelemetry refers to the measurement of physiological phenomena at a distance from where they occur (44). Practically, biotelemetry techniques can be designed to leave the subject in a relatively more normal psychological and physiological situation. Interference with normal movement patterns can be minimized and the

subject can be separated from the examining apparatus by relatively large distances, yet, still be fully monitored. Cinematographical and electromyographical techniques can be modified to this end.

Electromyography (EMG) refers to the graphic representation of the electrical activity of muscles (17). The task in biotelemetry of EMG is to accurately transmit the messages of electrical activity over distances to points where they can be recorded and/or interpreted, with minimal physical hindrance to the subject.

Cinematographical procedures permit the subject's unhampered activities to be recorded under relatively natural conditions. The film provides a permanent record for detailed analysis and makes it possible to evaluate the mechanics of complex physical activities (52, 65).

III. BIOTELEMETRY TECHNIQUES

Biotelemetry of the electromyogram has involved several techniques, each of which has particular advantages and disadvantages. A primary objective here has been to maximize both the quality of the EMG and subject freedom of movement, two factors which tend to be inversely related.

1. Radiotelemetry Systems

Radiotelemetry utilizes electromagnetic energy to transmit information over a distance. Radiotransmitters of varying dimensions and transmission capabilities have been attached to the subject to transmit the electromyogram, while a separate radioreceiver was located at a stationary point to receive the transmitted signal (8,9,29,42,57,60,61,66).

To date radiotelemetry investigations have generally been confined to simple activities such as walking and stair climbing. Subjects have often been restricted to movement along a narrow corridor, moving toward or away from a receiving antenna. Only Lewillie (60,61) examined subjects engaged in a more strenuous activity, swimming, and in a relatively normal environment, swimming pool. None of the studies reviewed attempted to examine EMG in a competitive situation.

Moore et al. (66) and Baumann and Hänggi (9) utilized miniature radiotransmitters, 225 g and 18 g, respectively, attached to the subject near their respective electrodes. Dubo et al. (29) utilized a belt mounted transmitter, Goldkamp (41) utilized a transmitter which was 'appropriately strapped to the body of the subject' and Walmsley (99) utilized a 'box containing the telemetry system'. Battye and Joseph (8) and Joseph and Watson (57) utilized an FM radiotransmitter strapped to the subject's back between the shoulders with one aerial going diagonally up past each shoulder. In all of these cases dimensional information concerning the FM radiotransmitters was not provided.

The majority of studies reviewed utilized radiotransmitters which were capable of single channel transmission of only one electromyogram (8,9,42,57,66). Dubo et al. (29) with four channels of EMG and two channels of time-event synchronization, Walmsley (99) with two channels of EMG and Lewillie (60,61) with one channel of EMG and one channel of electrogoniometry, were the only studies which indicated that they transmitted more than one channel of information per radiotransmitter. Maximum effective transmitter range has been given as 50 m, in the open

air (8,57), but is frequently unspecified.

Synchronization of Radiotelemetry and Cinematography: The radiotelemetry investigations reviewed did not use pictorial or cine film records for detailed biomechanical analysis. Rather these records were used only to provide a gross indication of subject activity at that instant in time. Battye and Joseph (8) and Joseph and Watson (57) utilized separate flash photographs to reconstruct ambulatory and stair climbing activities, respectively. The flash occurrence was electronically marked on the electromyogram. Moore et al. (66) utilized electrogoniometry to synchronize EMG and activity, while Walmsley (99) utilized foot-contact switches attached to the subject's shoe. In both cases an electrical connection from the subject to a central recording station was necessary. Although EMG was by radiotelemetry, the subject was not totally free of electrical connections. Only Lewillie (60,61) synchronized radiotelemetry of EMG and radiotelemetry of electrogoniometry.

Dubo et al. (29) used a polaroid camera to photograph four electromyograms, plus foot-contact switch information, displayed on an oscilloscope. Videotape records of subject activity were not correlated with EMG and were not subjected to temporal or spatial analysis.

Baumann and Hänggi (9) recorded EMG activity on an FM tape recorder and subject activity by means of two synchronized movie cameras. A picture numbering device indicated each shutter opening impulse on the magnetic tape and was used to match 16 mm film and the FM tape record of the EMG.

Assessment of Radiotelemetry: Radiotelemetry techniques can

eliminate the need for electrical connections to the subject. However, several other factors must be considered:

1. Low power radiotelementry equipment is necessary to meet government regulations on spurious radiation emmissions. Such equipment is difficult to set up and is highly dependent on antenna positioning if reliability is to be obtained over a wide area (89). In a study directed at radiotelemetry of the electrocardiogram, Powell and Walker (80) commented that it was impossible to devise antenna locations that would not allow foreign bodies to come between the transmitter and the receiving antenna. Once direct line of sight transmission was broken, electrical noise tended to obscure the recording.

2. A wide bandwidth FM transmitter and receiver are required for each channel of information recorded. If frequency or time multiplexing, sharing, are employed compromises in both fidelity and complexity of the transmitted message result (89).

3. Records are subject to considerable noise interference because the receiver takes in all available electromagnetic energy in the approximate pre-set range. The baseline drift, which often results, complicates the interpretation of the electromyogram.

4. The radiotransmitter equipment available for EMG is sufficiently large that it may interfere with normal movement patterns and does pose a danger to the wearer and other participants should it be used in a competitive situation.

2. Portable Recording Systems

In an effort to eliminate the need for costly and often unreliable radiotelemetry apparatus Brandell et al. (11) and Dommasch

et al. (27) developed the muscle electronic recording device (MERD). MERD is a small, modified tape recorder measuring 5 cm by 15 cm by 20 cm, which is strapped to the back of the subject. Initially MERD weighed 2 kg and could record two EMG channels simultaneously (11). A later version weighted 3.2 kg and was capable of recording EMG on six channels simultaneously (27). The play-back unit, part of MERD, later changed the recorded FM signals on the magnetic tape back to a replica of the original EMG signal for oscilloscope display.

Synchronization of MERD and Cinematography: Initially Brandell et al. (11) utilized a foot-contact switch connected to MERD. This switch was designed to fire almost exactly in the middle of the foot flat position of the running stride and leave a marker signal on one of the two MERD recording channels. The foot-contact switch also activated a light which was attached to MERD, and which was recorded on 16 mm film. However, as the speed of the runner increased the foot-contact switch made multiple firings and could not be used in analysis. Fortunately, a hand held switch was used to signal the terminal strides, thus permitting some synchronization of MERD and cinematography.

In later investigations the subject wore an arm band which contained two light sources and faced the camera (12,13,14,27). This light source was connected to MERD so that each time the light flashed a mark appeared on the synchronization channel, approximately four times per second. The subject also carried a hand held switch marker connected to MERD. By pushing the button of this switch a brief disruption of the synchronization channel resulted along with a light signal and the beginning and ending of activity could be signaled by the subject. Therefore, any frame of 16 mm film could

be traced to its respective electromyogram by relating light blinks on the cinefilm to the light synchronization marks on the recording tape, after these had been related to the disruption signal. Camera speeds varied from 50 fps (15) and 64 fps (12) for walking, to 80 fps (15) and 124 fps (11) for running.

Assessment of Portable Recording Systems: MERD has been used successfully during both running and walking activities, overground and on a motor driven treadmill. Although it is capable of recording EMG during vigorous activity, use during competitive situations is questionable, as is its physical influence on the subject's normal activity patterns, eg. posture, balance, gait. For this reason Brandell (15) removed both the light source and MERD itself from the subject, attaching them to nearby supports.

MERD does not utilize radiotelemetry. Consequently, range is not limited by transmitter or receiver capability. As well, electrical connections to the subject are unnecessary. However, synchronization of MERD and cinematography is dependent on camera visualization of a light source on the subject, or elsewhere in the camera's field of view. Thus, range is limited to camera lens resolution.

3. The Trailing Wire Method

To date, the majority of gait oriented studies utilizing EMG have employed electrode cables of various lengths connecting the subject to a central recording station. The extent to which the subject could move away from the EMG recording unit or be physically active was largely dependent on the number of active electrodes, the length of electrode cable and the capabilities of the EMG system.

Generally, subject excursion has been limited to less than five meters (43,49,63,85).

Hirschberg and Nathanson (49) utilized surface electrodes and a 3 m length of electrode cable to examine, simultaneously, seven lower extremity muscles during normal and handicapped forward walking. The electrode cable connected to a box attached to the subject's back and an assistant walked behind the subject carrying the electrode cable.

Close and Todd (21) recorded EMG activity, during normal forward walking and following tendon transfer procedures, both oscilloscopically and with a 16 mm sound motion picture camera that also recorded subject activity photographically. Only one muscle was examined at one time using dual internal wire electrodes and a shielded cable of unspecified length.

Gray and Basmajian (43) utilized fine wire electrodes and a 4.6 m length of 'Cicoil' flexible, multiwire cable to convey three channels of EMG and three channels of foot-contact data in the examination of normal and flat feet during normal forward walking.

Margora et al. (63) and Rozin et al. (85) combined information from three foot-contact switches, three electrogoniometers and four coaxial needle electrodes to investigate normal forward walking. The degree of discomfort associated with the teflon coated coaxial needle electrodes was reported to be generally low. However, it was not possible to examine the hamstring muscles owing to the large excursion of the needle within the muscle during contraction, and the resultant pain and altered gait pattern. The electrode cable and other feedback cables were suspended from an overhead frame, 4 m in radius, so that the

subject could walk up to 7 m unhindered.

Sutherland et al. (91,92,93) utilized three pairs of wire electrodes and an electrode cable of approximately 4.1 m length to examine lower extremity muscular activity during normal and handicapped gaits. The electrode cable was suspended by an overhead pulley to free the subjects' arms during forward walking.

With the objectives of avoiding the interference and the poor recording associated with radiotelemetry and the physical encumbrance of portable recording systems, Sprigings (88) utilized a special adaptation of the trailing wire method. EMG signals were transmitted over a one hundred foot length of electrode cable with relative absence of artifacts and minimal physical impediment to the running subject.

A special belt mounted pre-amplifier unit, 12.7 cm by 6.5 cm by 4.0 cm, weighing 0.23 kg, was capable of driving four EMG channels simultaneously over the entire length of multiconductor cable without coupling of conductors within the cable during periods of high activity. Figure 1 illustrates the trailing wire method as modified by Sprigings (88) to investigate the muscular pattern of running at speeds up to 17.7 kph over a level gym surface and on a motor driven treadmill.

Steadward (91) utilized the EMG system developed by Sprigings (88) to examine upper extremity muscular activity during various paraplegic activities including shot putting and wheelchair propulsion. All four of the EMG channels were utilized to convey EMG; none where required for synchronization of EMG and subject activity.

Synchronization of EMG and Physical Activity: Foot-contact

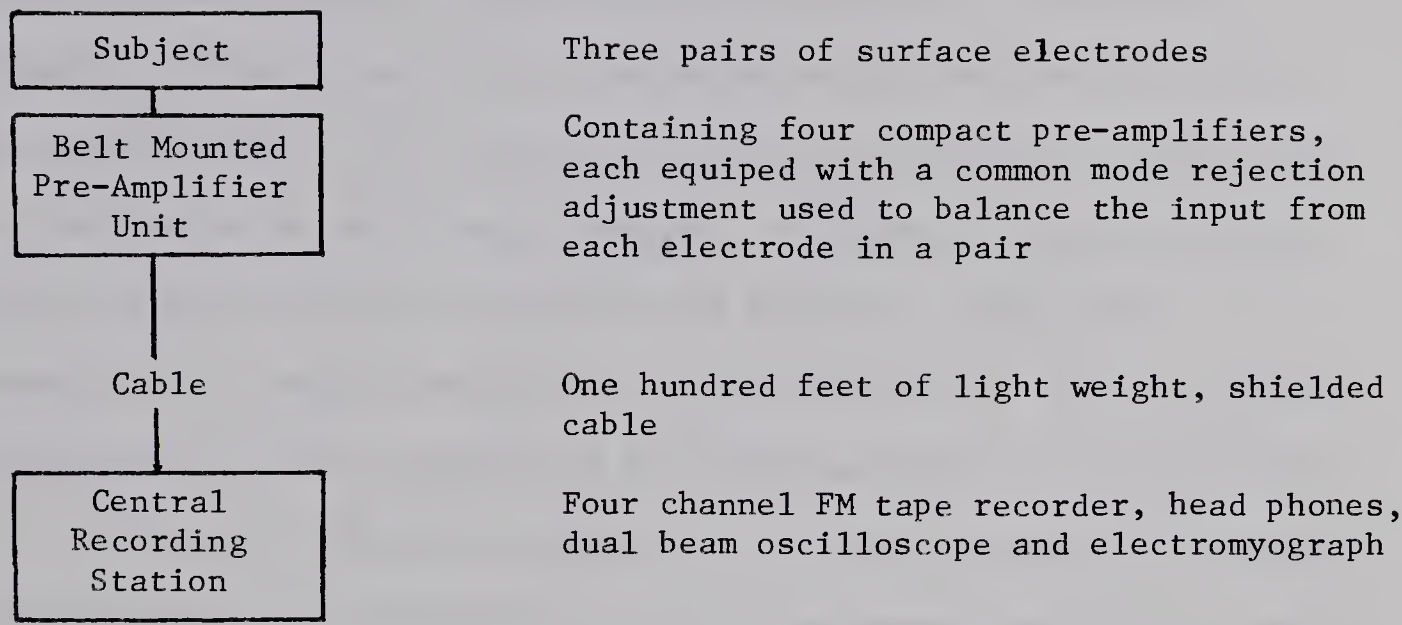


Figure 1. Schematic illustration of the trailing wire method as utilized by Sprigings (88). The EMG record on the FM tape was later played back to obtain the paper print-out.

switches attached to one of the subjects' shoes have been the most commonly utilized techniques for the synchronization of the electromyogram and subject activity (43,49,63,85). Closures of the foot-contact switches produced a simultaneous mark on one of the recording channels. Margora et al. (63) and Rozin et al. (85) also synchronized EMG and foot-contact data with simultaneous electrogoniometry of the hip, knee and ankle. All data was available on one print-out. Gray and Basmajian (43) also synchronized foot-contact switch data with 8 mm movies of the subjects' lower extremities. A specially adapted Fairchild Cinephonic Camera was used to film foot activity, as well as

to record single electromyograms along its magnetic tape audio edge. This was accomplished by connecting the receptacle of the camera, normally for microphone, to the individual monitoring outlets of the EMG during filming. When the movie film was played back the EMG could be displayed on an oscilloscope screen. By matching this audio edge electromyogram with its paper print-out duplicate, which also contained foot-contact switch data, synchronization of EMG and cinefilm was obtained for the remainder of the electromyograms on the print-out.

Close and Todd (21) utilized a continuous recording 35 mm camera to photograph a single oscilloscope electromyogram. The vertical output of the oscilloscope was connected to the amplifier of a 16 mm sound motion picture camera, which photographed the subject during normal forward walking. When the sound film was played back the magnetic tape recorded electromyogram, along its audio edge, could be displayed on an oscilloscope. By matching this play-back oscilloscope electromyogram with that recorded on 35 mm film, the 16 mm film, containing the record of subject activity, could be precisely related to the EMG at that instant in time.

Sutherland et al. (91,92,93) and Vreeland et al. (97) described a means of superimposing electromyograms directly on 16 mm film of the active subject. A silvered mirror system (Figure 2) was utilized to superimpose electromyograms onto 16 mm movie film so that each individual frame of film carried the three oscilloscope channels of EMG identical in time with the image of the subject shown. The Bolex camera, oscilloscope and mirror system were mounted on a turntable which was rotated to photograph the subject who walked along a tangent to a circle centered at the camera, 4.1 m radius. The image from the oscilloscope was projected optically via a fully silvered mirror into the lens of the

16 mm movie camera. The camera aimed through the half-silvered mirror to photograph simultaneously the walking subject and the three oscilloscope images on one frame of film.

The mirrors were placed at 45 degrees to the longitudinal axis of the camera lens and the oscilloscope. A camera speed of 64 fps and

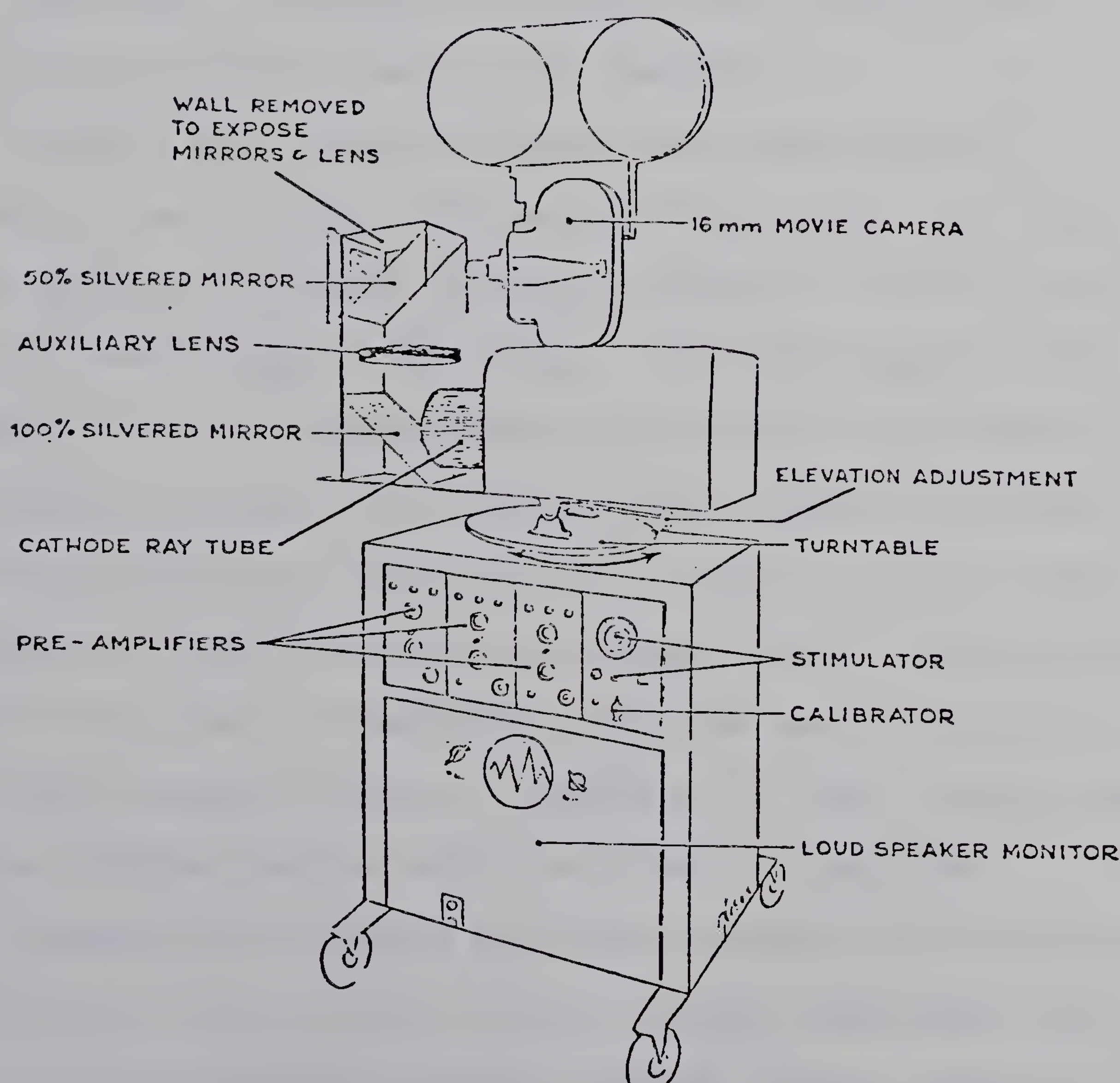


Figure 2. EMG - Cinematography synchronization via silvered mirror system (91).

an oscilloscope sweep speed of three seconds were the settings utilized. A P7 phosphor, with a decay time in excess of one second, provided the three oscilloscope traces. The camera shutter angle reported was 180 degrees and exposure time 1/128th sec (92).

Flint and Gudgell (39) utilized a similar silvered mirror system to simultaneously record three channels of oscilloscope electromyograms, a data board, a timing clock and a subject performing abdominal exercises. All film records were made at 12 fps, with oscilloscope sweep speeds of 2.3 and 3.0 milliseconds per cm, and using surface electrodes. The length of electrode cable, subject-camera distance and film exposure time were not specified.

Sprigings (88) utilized internal camera timing lights to synchronize EMG and cinefilm. The internal timing lights left a light trace on the edge of the 16 mm film and simultaneous triggered an event mark on the fourth channel of the FM tape. Particular frames of film were related to their respective EMG by counting back, first along the synchronizing pulse marks on the electromyogram, and then calculating the distance from the last pulse mark to the frame of interest. Owing to the distance between the camera gate, exposed frame of film, and the location of the interval timing lights within the camera, the interval timing pulses preceded the frame of interest by 14 frames. Camera speed was 70 fps, exposure time and shutter angle were not specified.

Steadward (90) utilized a split-lens, one-half section close-up lens and one-half section regular filter, to permit simultaneous sharp focus on a near-by oscilloscope and on a distant subject. The frames of 16 mm film were divided in half such that the left half illustrated the active subject, while the right half carried the oscilloscope face

and the four electromyograms. Camera speed was 64 fps shutter angle was 45 degrees and an exposure time of 1/512th second was utilized per frame of film. The oscilloscope sweep speed utilized was 5 milliseconds per centimeter.

Assessment of The Trailing Wire Method: The trailing wire method has been the most popular investigative technique for EMG during walking. Unlike radiotelemetry or portable recording systems, the subject is connected to the EMG recording apparatus by an electrode cable. This cable does hinder mobility and does preclude investigation under competitive conditions, particularly team competitions. However, no transmitting antenna is required and the subject can move anywhere in the area which the cable permits. As well, he need not carry a bulky recorder on his back.

Subjects have been held relatively close, generally within five meters, to the recording apparatus. In order to increase this distance it is necessary for the subject to carry a pre-amplifier designed to drive clean EMG signals. Trailing wire systems are generally acknowledged to give good quality recordings, owing to a minimum of electromagnetic interference, and are adaptable to a variety of synchronization techniques.

The system described by Sprigings (88,89) has been particularly effective in limiting the physical encumbrance to the subject. It is also capable of minimizing 60 Hz interference and balancing the level of input from each electrode in a pair. The subject can be separated from the examining apparatus by up to one hundred feet and can carry out vigorous activity without diminishing the quality of records.

4. Synchronization of Electromyography and Physical Activity

The simple use of electromyography provides insufficient

information from which to interpret muscle actions in specific skilled movements (3). Synchronized EMG - physical activity records are essential if correlations are to be drawn between the two, but such records must be interpreted in light of various inherent limitations. Several methods for synchronizing EMG and activity have already been outlined in reference to gait studies. Many other synchronization techniques exist, but will not be elaborated upon here.

A few, of the many synchronization techniques employed are as follows: electrogoniometry (60,61,63,66,85), flash photographs (8,57), electronic flash units within the camera itself (56), interval timing lights within the camera (88), flashing lights attached to the subject (12,13,14), flashing lights placed within the camera's field of view (15), hand operated electronic markers (11,12), electronic foot-contact switch indicators (29,30,45,49,62,99), revolving discs placed within the camera's field of view (40), modifications of the camera film counterdrive (10), superimposing EMG directly onto movie film of the active subject by means of a silvered mirror system (39,91,92,93,94), superimposing without the silvered mirror system using a specially adapted camera (95), photographing the electromyogram with a separate camera (21) and use of a split lens to place both subject activity and electromyograms on the same frame of film (90).

Only the superimposing and the split lens techniques eliminated the need for two separate records - the electromyogram and the physical activity record - which required further correlation. Only one record is necessary and the subject can be relieved of many hindersome mechanical devices, such as electrogoniometers, flashing lights and foot-contact switches. However, mirror systems require more light on the subject to develop the film exposed through a half-silvered mirror. The subject and the

oscilloscope electromyograms cannot both be in perfect focus because camera depth of field is insufficiently large to accompany both. As well, a dark background behind the subject and in the oscilloscope area are necessary to provide enough contrast so that the oscilloscope traces can be adequately recorded on film. The technique utilizing a Hycam camera equipped with two lenses, the front lens photographs the subject while the back lens photographs the oscilloscope tracings (95), appears to be the most practical, but it is also the most expensive synchronization technique. The split lens technique divides each frame of film so that the subject and the electromyograms share the frame. Consequently, the film image size in both cases is reduced and the subject has a smaller portion of the camera's field of view in which to be active.

Although numerous EMG - physical activity synchronization techniques have been utilized, it is apparent that no one technique can be ideal under experimental conditions.

IV. WALKING

As previously stated, the biomechanical analysis of backward walking has received only cursory attention in the available literature. Consequently, a discussion of forward walking is presented here because many of the principles and research methodologies involved relate directly to backward walking, as well as forward walking.

Biomechanically, human locomotion is considered under two broad headings:

1. Kinematics deals with bodies in motion, without regard to the

forces acting to produce the motion. It describes the position of a body in space at a particular time and the motion of body parts relative to one another. Kinematics is essentially space-time analysis.

2. Kinetics deals with the forces acting on bodies to produce or alter motion, such as internally the muscles and externally gravity and friction (30,33,47,59).

1. Introduction

Considerable research, effort and discussion has centered on normal forward walking. As well, considerable discussion focuses daily on the clinical evaluation of walking styles. Throughout, one persistent problem remains, the inconsistency with which many descriptive terms have been utilized. Although frequently used interchangeably, these terms are not truly synonymous. Their appropriate meanings are outlined below (1):

Locomotion - refers to movement from one place to another and may be classified as creeping, crawling, brachial, quadrupedal and bipedal

Walking - refers to progression on foot

Gait - refers to the manner of style of walking, such as antalgic, ataxic, paralytic and orthograde

Ambulant - refers to the ability to walk, not confined to bed.

Although largely taken for granted bipedal locomotion, with an orthograde gait (or normal walking) is an extremely complicated process. The illusion of simplicity stems from the speed and coordination with which millions of energy transformations are controlled to produce or to prevent movement at almost every major joint in the body, in order to take just one step (75). Walking

forwards is not simply an act of falling forward and catching oneself.

Normal gait involves the transformation of a series of controlled and coordinated angular motions occurring simultaneously at the various joints of the lower extremities into a smooth path of motion for the center of gravity (C of G) of the body as a whole (81). The ability to maintain posture and to walk successfully under a wide variety of circumstances depends not only on the precision of intact muscle and joint structures, but also on the integration made possible by a complex nervous system (28,83) and many years of practice. The characteristic patterns that are seen in the adult are not achieved until a child reaches seven to nine years of age (54,86).

There are a multitude of actions related to advancing the body in a smooth and economical manner (77). Each individual displays certain peculiarities which are superimposed on the basic pattern of walking (54). The wide spectrum of 'normal' gaits which exists might be partially attributed to factors such as body build, age, sex, occupation, nationality and geographic location (28). The walking pattern exhibited by each individual represents his solution to the problem of how to get from one place to another with minimum effort, adequate stability and acceptable appearance (32).

2. Functional Tasks in Walking

Normal forward walking, as commonly described, is a stridding gait (83). In order to permit this pattern three functional tasks must be accomplished simultaneously: forward progression, single limb balance and limb length adjustment. Perry (77) outlined these functional tasks as follows:

1. Forward Progression refers to the advancement of the body in a smooth and economical manner and involves primarily the following mechanical tasks: shock absorption related to a rapid transfer of weight onto the forward foot, control of movement that threatens the stability of the limb as a weight bearing structure and generation of sufficient force to carry the body forward (forward propulsion). By utilizing momentum to assist in shock absorption and in propelling the body forward, the work requirements of forward progression are minimized.

2. Single Limb Balance refers to the ability to balance the body over one limb while swinging the other limb forward. Without such balance, or an adequate substitute, such as a crutch or a cane, orthograde bipedal locomotion is impossible. In the normal standing posture the trunk is centered between the two supporting limbs. As soon as one foot is lifted the body becomes grossly off balance owing to the loss of one of its supports. To prevent falling and permit forward progression a massive holding force from the hip abductor muscles, as well as a lateral body shift over the weight bearing foot, is necessary.

3. Limb Length Adjustment involves the relative lengthening and shortening of the limbs to enable the foot to reach the ground with ease, whether the extremity is directed straight downward, or is reaching forward or backward. If the limb is reaching forward or backward, that limb must be longer than the limb which is providing vertical support. Failure to make a limb length adjustment and simply drop the body down as it passes over the forward foot is potentially detrimental. The jarring action as the body drops is uncomfortable

and such a drop would cause an abrupt change in direction and hence loss of forward momentum that might otherwise be harnessed for forward travel.

The accomplishment of all three tasks during each walking cycle permits a smooth ride for the body and minimizes energy expenditure (77).

3. Terms Defining Normal Walking

Walking versus Running: During walking at least one foot is always in contact with the ground and there are periods during which both feet are in ground contact (double limb support). During running there are periods during which one foot is in contact with the ground and during which neither foot is in contact with the ground, but at no time are both feet in contact with the ground (69,75,102). Running might be described as a series of smoothly coordinated jumps during which the body weight is borne on one foot, becomes airborne, is then carried on the opposite foot and again becomes airborne (70).

Component Phases of Walking: The alternate standing and stepping aspects of normal forward walking are technically defined as the stance and the swing phases, respectively. To better identify and isolate related events within each, both stance and swing phases have been divided into sub-phases, each of which involves a complex of activity related to accomplishing a particular task (77). Each task is a composite of the appropriate components of forward progression, single limb balance and limb length adjustment (Figures 3 and 4) (43,77,83). Analysis of normal walking is generally confined to one leg at a time.

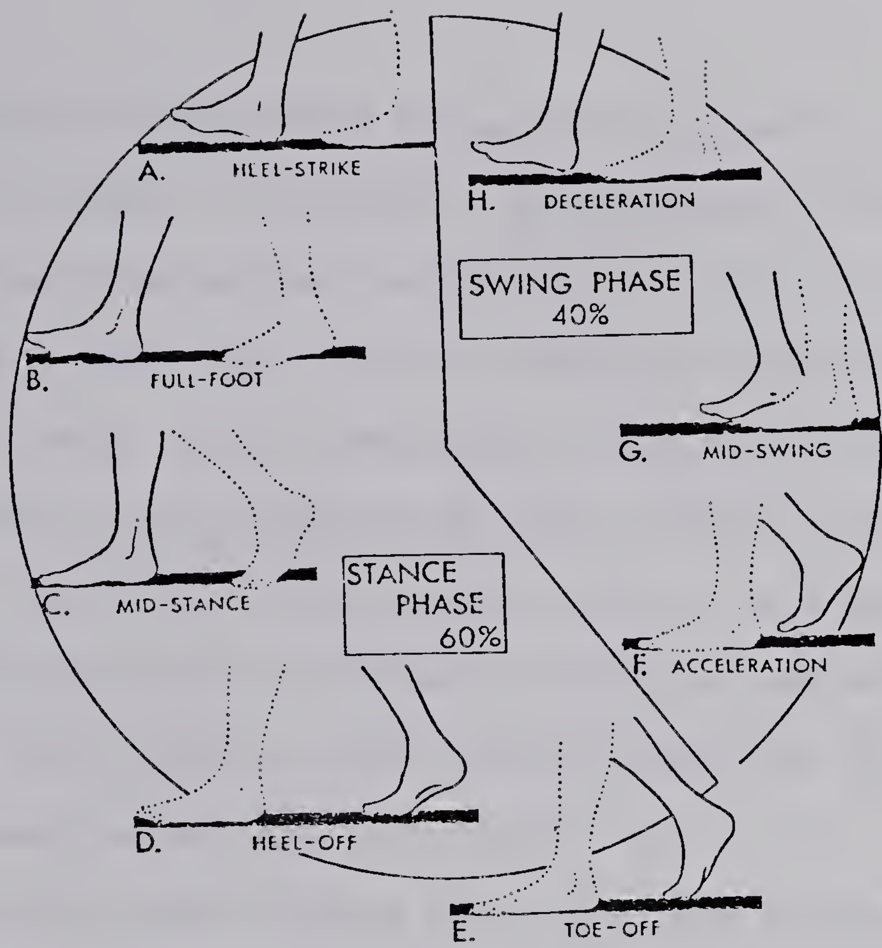


Figure 3. Diagramatic illustration of the component phases of a single forward walking cycle (43). Gray and Basmajian (43) are the only authors to use the term 'full-foot instead of foot-flat.

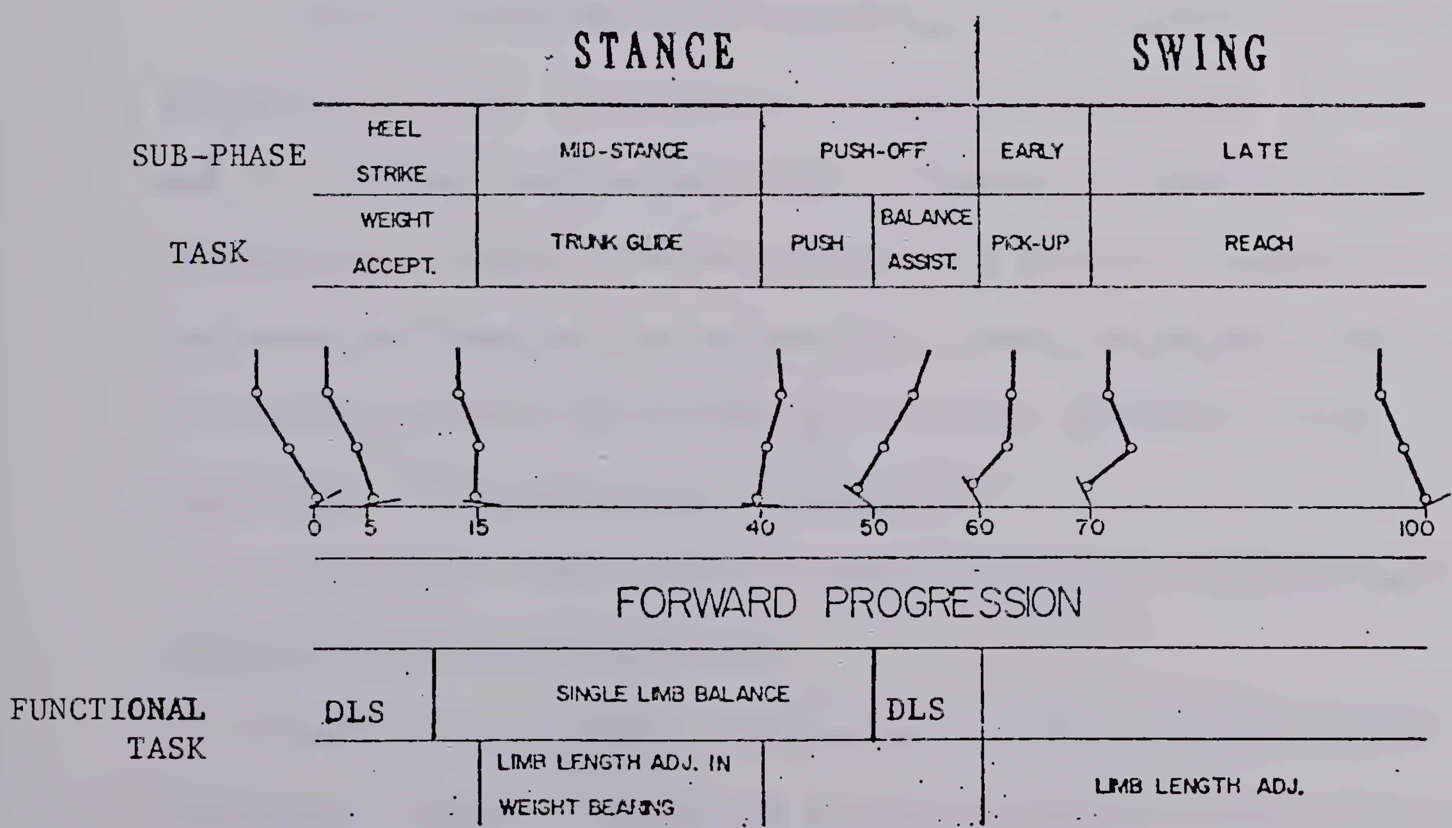


Figure 4. Schematic illustration of the inter-relationships between forward progression, single limb balance, limb length adjustment and the sub-divisions of the forward walking cycle (77). The term single limb balance has been modified, by this author, from the manner in which it appeared in the original diagram, in order to illustrate two double limb support (DLS) periods before and after the single limb support period.

Stance Phase is that period during which the foot is in contact with the ground. It begins at the instant that the heel strikes the ground (heel-strike) and ends at the instant that ground contact is broken with that foot (toe-off). The limb then swings forward toward the next heel-strike (27,28,59,71,75,77,81).

Swing Phase is that period during which the foot is off the ground moving forward toward the next heel-strike. It begins at the instant that ground contact is broken (toe-off) and ends at the instant that ground contact is again made with that foot (heel-strike), after having swung forward (28,70,75,77,81).

During normal forward walking the stance phase occupies approximately 60% of the walking cycle and the swing phase occupies approximately 40%. However, the relative durations of these two phases may be altered by the cadence of the walk (43,75,83).

The two phases of normal bipedal gait have been divided into sub-phases in order to facilitate biomechanical analysis (Figures 3 and 4). Although many authors have discussed the forward walking cycle in great detail, few have defined the various sub-phases or the events utilized as the boundaries of these sub-phases. Specific occurrences, such as the following, have been utilizied as the boundaries of the sub-phases (27,59,67,75):

1. Heel-Strike - the instant at which the heel of the previously swinging leg contacts the ground

2. Foot-Flat (Toe-Down) - the instant at which the toe contacts the ground, such that the entire sole of the foot is now in ground contact

3. Mid-Swing - the instant the axis through the malleoli of the swinging leg crosses the frontal plane in which the axis through the malleoli of the standing leg lies (75)

4. Heel-Off - the instant at which the heel breaks contact with the ground, the toes remaining in ground contact

5. Toe-Off - the instant at which the toes break contact with the ground.

Only Peizer et al. (75) defined mid-swing as above, an instant in time. Perry (77) did not define mid-swing as an instant in time, but did suggest that it was the termination of knee flexion.

Sub-Phases of Stance Phase (59,77)

1. Heel-Strike Sub-Phase - begins at heel-strike and ends at foot-flat. It is a period of weight transference onto the new stance leg.

2. Mid-Stance Sub-Phase - begins at foot-flat and ends at heel-off. It is primarily a period of single limb support during which the entire sole of the stance foot is in ground contact.

3. Push-Off Sub-Phase - begins at heel-off and ends at toe-off. During this period the body is propelled forward by the forceful action of the calf muscles (75).

Sub-Phases of Swing Phase (77)

1. Early Swing Sub-Phase - begins at toe-off and ends at mid-swing. The forward swinging leg catches up to the stance leg at mid-swing.

2. Late Swing Sub-Phase - begins at mid-swing and ends at heel-strike. The forward swinging leg reaches ahead of the stance leg toward the next ground contact.

The sub-phases of swing phase have also been classified as acceleration, mid-swing and deceleration (43,59,67,75). These terms

have been described as follows:

1. Acceleration Sub-Phase - that period following toe-off, during which the swinging leg commences to travel through space. At this point in time the swinging leg must be accelerated in order to catch up to and get in front of the body in preparation for the next heel-strike.

2. Mid-Swing Sub-Phase - that period during which the contralateral leg is fully supporting the body weight and the ipsilateral leg is starting to extend at the knee preparing to heel-strike. The swinging leg has caught up to and passes directly beneath the body.

3. Deceleration Sub-Phase - that period just prior to heel-strike during which the swinging leg begins to stop its forward travel through space and is in the reach position preparatory for weight acceptance. The forward momentum of the leg is restrained to control the position and velocity of the foot immediately before heel-strike.

In this second classification system the lack of specificity in terms of assigning boundaries to the sub-phases makes distinction between sub-phases unclear, particularly distinction with the naked eye. Also, mid-swing is not defined as an instant in time, but as a sub-phase with no clear boundaries.

Perry (78) has outlined a more versatile terminology designed to describe the gait of both normal and handicapped individuals. This non-anatomically based terminology is illustrated in Chapter Five of the present investigation.

Other Terms Describing The Walking Cycle: The walking cycle extends from heel-strike of one foot to the next heel-strike of the

same foot, one stance and one swing phase. Walking cycle duration is inversely related to cadence and involves two double limb support periods (75,83). The opposite leg moves in a reciprocal manner during its simultaneously occurring, but out-of-phase walking cycle.

Double Limb Support refers to those periods of time during which both feet are simultaneously in contact with the ground. In normal walking the stance phases of the two legs overlap so that the periods of double limb support occupy approximately 25% of the walking cycle (33,81).

Stride Length refers to the linear distance in the plane of progression between successive floor-to-floor contacts of the same foot.

Step Length refers to the linear distance between successive floor-contact points of opposite feet (69,70).

Stride Time refers to the time elapsed between successive floor-to-floor contacts of the same foot. It is identical to walking cycle time or duration.

Cadence refers to the number of steps, or strides, per unit length of time. It may also be considered as the step, or stride frequency.

4. Dimensions of The Normal Walking Cycle

Many studies have concerned themselves with the temporal and spatial aspects of normal forward walking. However, few studies have provided detailed analysis of more than a few of the basic parameters descriptive of the normal forward walking cycle itself. Table I illustrates mean values of selected temporal and spatial parameters, based on a sample of thirty normal males (69). Table II illustrates a more frequently

TABLE I

Values For Selected Parameters of The Normal Forward Walking Cycle (69)

Parameter or Gait Component		Value Reported
Walking Speed (cm/sec)		151 (20)
Walking Cycle Duration (sec)		1.06 (0.09)
Stance Phase Duration	(sec)	0.65 (0.07)
	(per cent of cycle)	61
Swing Phase Duration	(sec)	0.41 (0.04)
	(per cent of cycle)	39
Stride Length (cm)		156 (13)

(   ) Standard Deviation

TABLE II

Forward Walking Cadences Reported In Previous Investigations

Author(s)	Description of Investigation	Cadence (steps/min)
Drills et al. 1958	936 persons timed over 20 yards on a New York City street	112 free speed
Murray et al. 1966	30 normal males, ages 20 to 65 years	113 free speed 138 fast speed
Murray 1967	60 normal males, ages 20 to 85 years	113 free speed 138 fast speed
Murray et al. 1969	64 normal males, ages 20 to 87 years	111 free speed 132 fast speed
Zuniga et al. 1973	20 normal males, mean age 36 years	89 free speed
	20 normal females, mean age 27 years	106 free speed
Winter et al. 1976	28 subjects, age and sex not specified	82 slow speed 93 free speed 114 fast speed
Dubo et al. 1976	20 normal males, ages 8 to 72 years, mean age 37 years	106 free speed

reported parameter, cadence.

5. Displacement of The Body Center of Gravity

The body center of gravity (C of G) is not a precise or fixed point. Its position at any instant in time is governed by the position of the body segments, as well as the distribution of body fluids and clothing (47,75). In the standing position the location of the body C of G is approximately one inch anterior to the second sacral vertebra and lies at approximately 55-56% of the body height, measured from the floor (86,102). Its displacement pattern may be regarded as constituting the summation or end result of all the forces and motions acting upon and concerned with the translation of the body from one point to another (28,86).

1. Vertical Displacement: The vertical path described by the body C of G during normal walking has been referred to as elliptical sinusoid stretched in the plane of progression (86). Within each walking cycle the body gently oscillates through two vertical peaks and two vertical valleys, which coincide closely with the lower limb positions in their times of occurrence (30,68,69,70,71,86).

The valleys occur during double limb support, when both feet are on the ground and the body weight is evenly distributed between them (75). At this time one limb is directed obliquely backwards and the other is outstretched obliquely forwards (70). The pelvis then begins to rise shortly after heel-strike (30).

The peaks occur during periods of single limb support, at mid-stance of alternate legs, also the middle of swing phase (86). At these instances, during mid-stance of alternate legs, the swinging leg is passing the supporting leg (30,75). Although the two

oscillations appear equal and symmetrical, the stance phase peak has been reported to be slightly greater (30). At its ambulatory summit the body C of G is slightly lower than in the erect standing position (86).

Vertical displacement has generally been described in reference to a fixed point on the body. Inman (54) stated that the vertical displacement measured at the top of the head is approximately the same as that measured at the sacrum. However, comparison of the vertical displacement patterns of the head or the sacrum with the calculated body C of G was not located in the literature examined. Peizer et al. (75) reported normal vertical displacement of a fixed point on the pelvis to be 5.08 cm. Inman (54) reported a vertical displacement of 4-5 cm measured at a point on the pelvis opposite the second sacral segment. Saunders et al. (86) reported a mean vertical displacement of 4.57 cm for the body C of G, but did not state how the C of G was determined. Eberhart et al. (30) reported a vertical oscillation of approximately 5.08 cm measured at the iliac crest. Murray et al. reported that the vertical displacement measured at the top of the head (71) and at a neck target averaged 4.8 ± 1.1 cm during free speed walking.

2. Lateral Displacement: As the body weight is transferred from one leg to the other there is a corresponding shift of the pelvis and trunk toward the weight bearing side (30,54,59). This displacement reaches it lateral limit at midstance of alternate legs and has been described as a smooth, oscillating curve which relates closely to the position of the lower extremities (54,55,69,86).

Peak-to-peak lateral displacements of approximately 5.08 cm

(30,31) and 4-5 cm (54) have been reported for a point near the body C of G. Saunders et al. (86) gave a value of 4.45 cm in reference to lateral pelvic displacement, while Murray et al. reported lateral displacements, measured at the head, of 6.0 $\pm$ 1.7 cm (68,71) and 5.9 $\pm$ 1.7 cm (69) during free speed, normal forward walking.

If the vertical and lateral displacements are combined and projected on the XY, or frontal plane they describe an almost perfect figure eight occupying approximately 5.08 cm square. The vertical and lateral deviations are also equal and symmetrical in both planes (86).

3. Forward Displacement: During the normal walking cycle the horizontal velocity of the body C of G in the plane of progression is almost constant, at 4 kph (2). However, under closer examination it is observed that the instantaneous velocity of the body C of G changes constantly as the body weight is applied to or removed from each foot successively (55,68,69,70,71).

The changes in horizontal velocity preclude visual perception because they are executed so smoothly. Horizontal velocity decreases slightly as the trunk climbs to its highest elevation during mid-stance. It then increases slightly as the trunk descends to its lowest level during double limb support (68,69,70). The horizontal velocity of the body C of G is characterized by a rhythmic lurching of non-uniform velocity as the body weight is shifted from one leg to the other (75). Horizontal velocity in the line of progression oscillates and is characterized by phases of gentle increase and decrease.

6. Energy Considerations

Normal forward walking conforms to the minimum energy expend-

iture principle. Fundamentally, it is the translation of the body C of G through space in a manner requiring the least expenditure of energy supplies (86). The body integrates the motion of the various segments of the body and controls the activity of muscles so as to minimize energy expenditure (54).

In terms of caloric expenditure normal forward walking is extremely efficient and no other common activity compares favorably. Walking speeds up to 6.4 kph require approximately 0.63 Cal/min/kph (75). Even minor alterations in the normal gait pattern increase energy expenditure and decrease efficiency (75).

To walk with a minimum of energy it is necessary to minimize the variations in the vertical, lateral and forward displacements of the body C of G. Abnormal displacements in any direction are accompanied by disproportionately high increases in the energy required to walk. The coordinated knee and ankle motions are the principle mechanisms by which the vertical displacement of the body C of G are limited (54).

The optimal speed for walking is a free or comfortable speed at which energy expenditure is minimal (46). It is the speed adopted 'naturally' by the subject under the particular circumstances (2,54). Walking speeds less than, or in excess of this 'free' or 'natural' speed result in increased energy useage (55). Nature's goal is to get from one place to another with the least expenditure of energy. Each individual employs whatever nature gave him in his attempt to do so (54,55).

7. Lower Extremity Joint Excursions

The excursions of the joints of the lower extremities during

normal forward walking have been described graphically by several investigators (12,15,30,63,68,69,70,71,75,85,92,95) and are illustrated in Figure 5. The significance of joint excursion information lies in the fact that the joints act to smooth the path of the body C of G and thus limit energy expenditure (30,33,54,75). As well, joint excursions are readily apparent to the trained observer and such information can readily be of value in gait training and re-education, particularly in the case of lower extremity amputees.

Normal forward walking is an example of general motion, translatory motion of the body as a whole is brought about by means of the angular motions of the lower extremities (102).

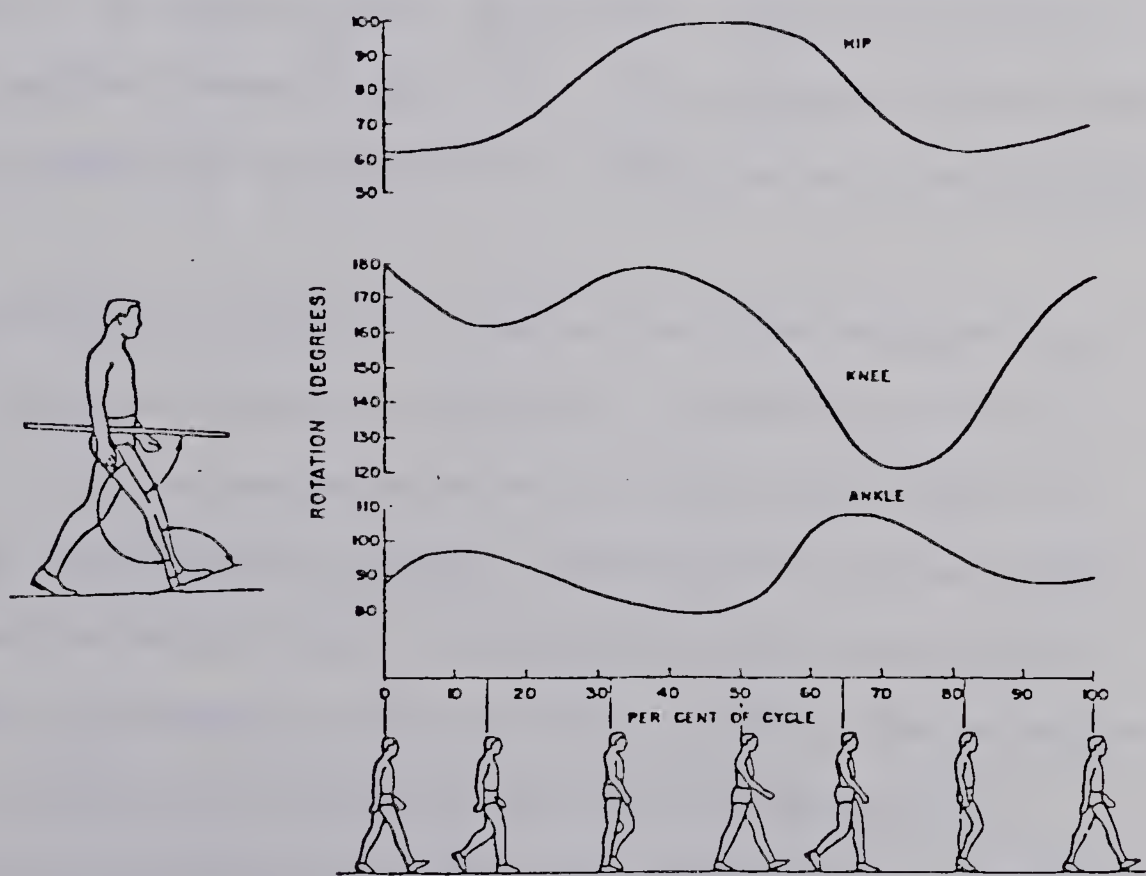


Figure 5. Hip, knee and ankle joint angles related to the forward walking cycle (75).

8. EMG Related To Walking

The rhythmic intermittent contractions of the muscles of the lower extremities during walking are related to the events of the walking cycle (Figures 6 and 7). If continuous electromyograms are recorded from individual muscles and synchronized with the physical activity at hand, a phasic description of the walking cycle is available (21,87). There exists uniformity of individual patterns of muscular activity (30).

It should be stressed that under normal conditions the EMG accurately portrays the timing, but not the force of muscle contraction (92). The visualization of peak muscle action potentials precedes the development of peak muscle tension by approximately 0.08 $\pm$ 0.02 sec (53). However, the muscle tension outlasts the electrical potentials (62,91). Electrode placement may effect the relationship between actual tension development and the appearance of muscle action potentials (62, 79).

Electromyography serves to illustrate the phase relationships of muscle actions and enables investigators to relate the muscular pattern of activity to the motion of the skeletal parts (Figure 7). Inspection of muscle activity patterns during forward walking reveals that most muscles act only once, over short periods of time and are silent during the remainder of the gait cycle (55,79). Muscles act to stabilize, accelerate and decelerate the lower extremities (30).

Walking is not solely the result of muscular activity. Rather, intrinsic muscular forces and extrinsic gravitational forces interact to produce or to prevent motion at the various joints of each segment of the body (30,75). During large intervals in the walking cycle the

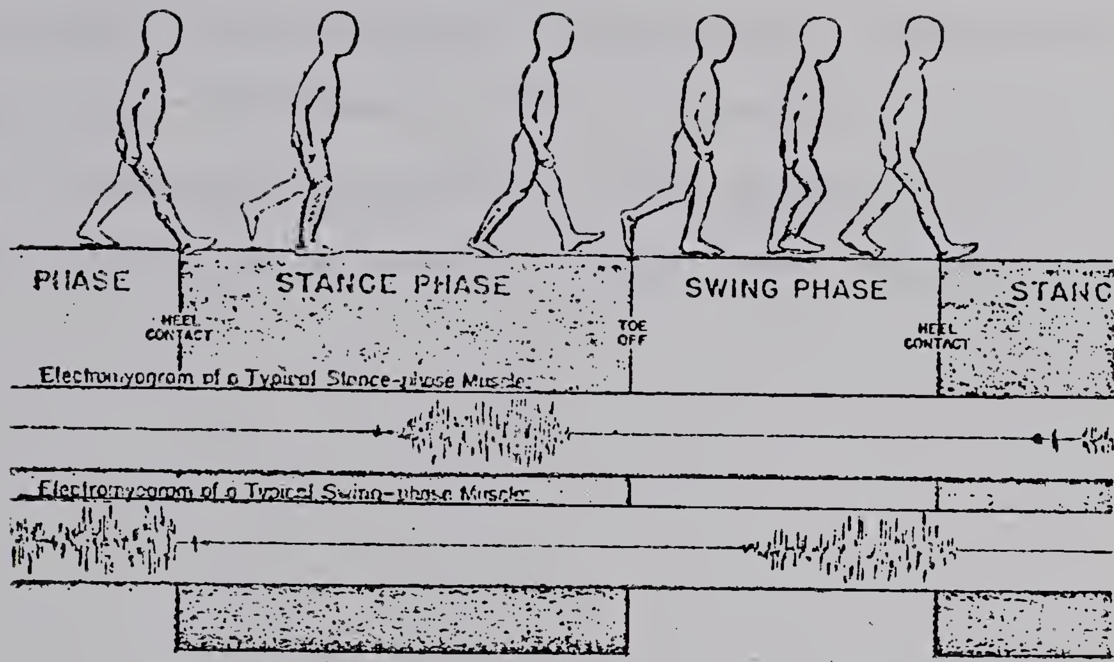


Figure 6. Diagramatic illustration of idealized electromyograms of stance and swing phase muscles (21).

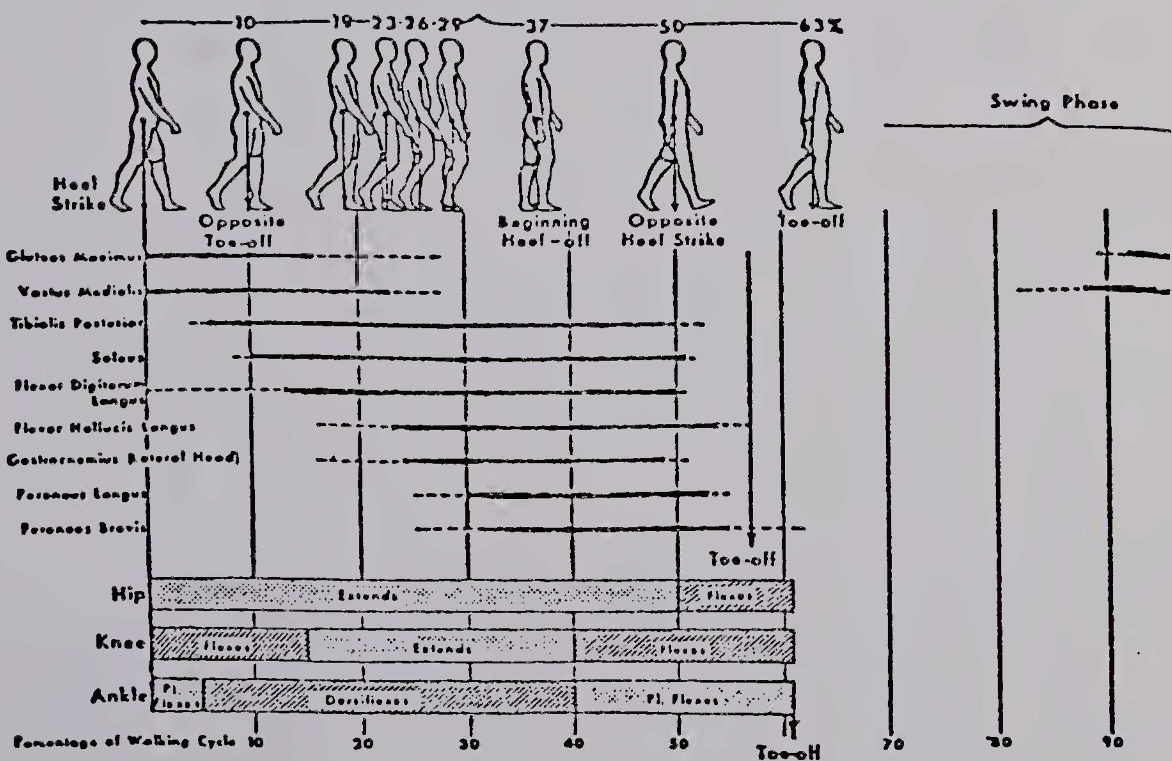


Fig. 1

Partial walking cycle—heel strike to toe-off—in normal adult male. Successive positions in one walking cycle of one of the control subjects, as recorded in motion pictures, are depicted by the manikins. The center of gravity of the body, statically determined, is shown for each position (circle indicates the center of gravity and vertical line, the direction of earth pull).

Cycles of muscle activity in normal control subjects are indicated by solid and broken lines. The solid lines indicate the means and the broken lines, the ranges. The numbers of subjects from whom data were obtained for each muscle were: flexor hallucis longus, three; flexor digitorum longus, five, peroneus brevis, five; peroneus longus, five; gastrocnemius (lateral head), five; soleus, five; tibialis posterior, four; vastus medialis, five (one showing no activity); gluteus maximus, six (two showing no activity).

Figure 7. Graphic representation of EMG and joint excursions related to the forward walking cycle, stance phase (91).

limb is carried forward solely by its own inertia (30). Electromyography must be supplemented with other biomechanical techniques, such as cinematography and electrical synchronization in order to correlate the EMG and the physical activity under consideration (3).

CHAPTER THREE

METHODS AND PROCEDURES

I. INTRODUCTION

The study combined the techniques of electromyography and cinematography to examine the temporal and spatial, as well as the muscular pattern of activity, of the lower extremities and the interrelationships of these factors during normal backward and forward walking at a free speed over a horizontal surface.

Electromyographic techniques were utilized to detect electrical activity in twelve lower extremity muscles and muscle groups, which were considered by the investigator to be relatively accessible via surface electromyography and which were also considered to be major contributors to normal backward walking. The muscles were the tibialis anterior, the peroneus longus, the gastrocnemius (medial head), the vastus medialis, the vastus lateralis, the rectus femoris, the hamstrings (as a group), the medial hamstrings, the lateral hamstrings, the gluteus maximus, the gluteus medius and the adductor longus.

Cinematographic procedures were utilized to determine the temporal and spatial relationships of the component phases and subphases of the backward and forward walking cycles, and their relationships to the muscular pattern of activity. Two synchronized film records provided permanent records of the temporal, spatial and electromyographic sequence of activity. One record illustrated only the lateral view of the subject, while the second illustrated both the anterior view and the four simultaneous electromyograms.

II. APPARATUS

1. Electromyograph (EMG)

The electrical pattern of muscular activity was detected by means of a specially designed EMG unit illustrated in Figure 8 (88,89). The subject wore a belt-mounted pre-amplifier, or remote transponder unit, measuring 12.7 cm by 6.5 cm by 4.0 cm and weighing 0.23 kg. This pre-amplifier unit contained four compact pre-amplifiers and was capable of driving four EMG channels simultaneously over the entire one hundred foot length of multi-conductor cable without coupling of conductors within the cable during periods of high electrical activity. The lightweight four conductor-shielded cable transmitted the EMG to a fixed amplifier and filtering system. The compactness of the pre-amplifier unit, combined with the light flexible nature of the electrode cable offered minimal physical impediment to the subject.

The pre-amplifier unit contained four common-mode balancing circuits which enabled the investigator to compensate for differences in skin contact resistance, tissue impedence and electrode impedence. In this way the electrodes of each pair were balanced with respect to initial levels of skin potention. The main EMG amplifier unit contained four 60 Hz notch filters, designed to minimize common 60 cycle interference. An integrator was not used. The raw electromyograms, or EMG signals, displayed on the Tektronix 564 Four Beam Oscilloscope (see Appendix B for a listing of equipment manufacturers) represented an interference pattern indicative of a summation of all the electrical activity in relatively large sections of muscle tissue (3,24,101).

Electrodes: Four pairs of collodian type, stainless steel

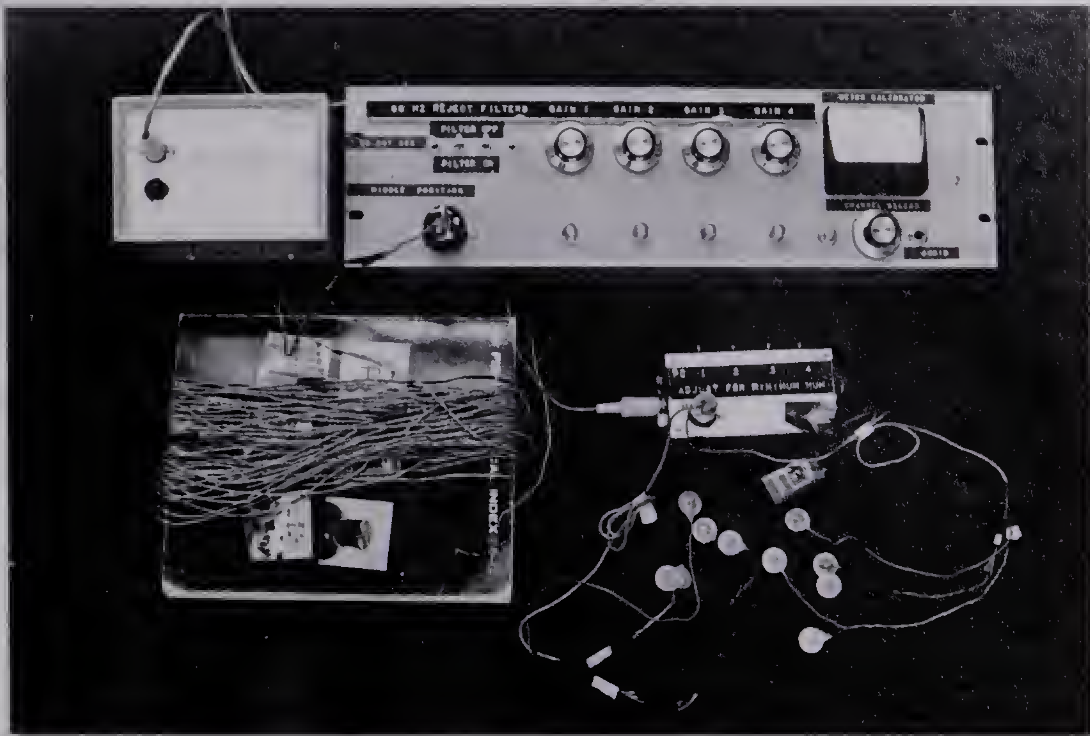


Figure 8. Electromyographical apparatus (left to right), top row: DC power pack and central amplifier unit; bottom row: electrode cable, pre-amplifier unit and electrodes.

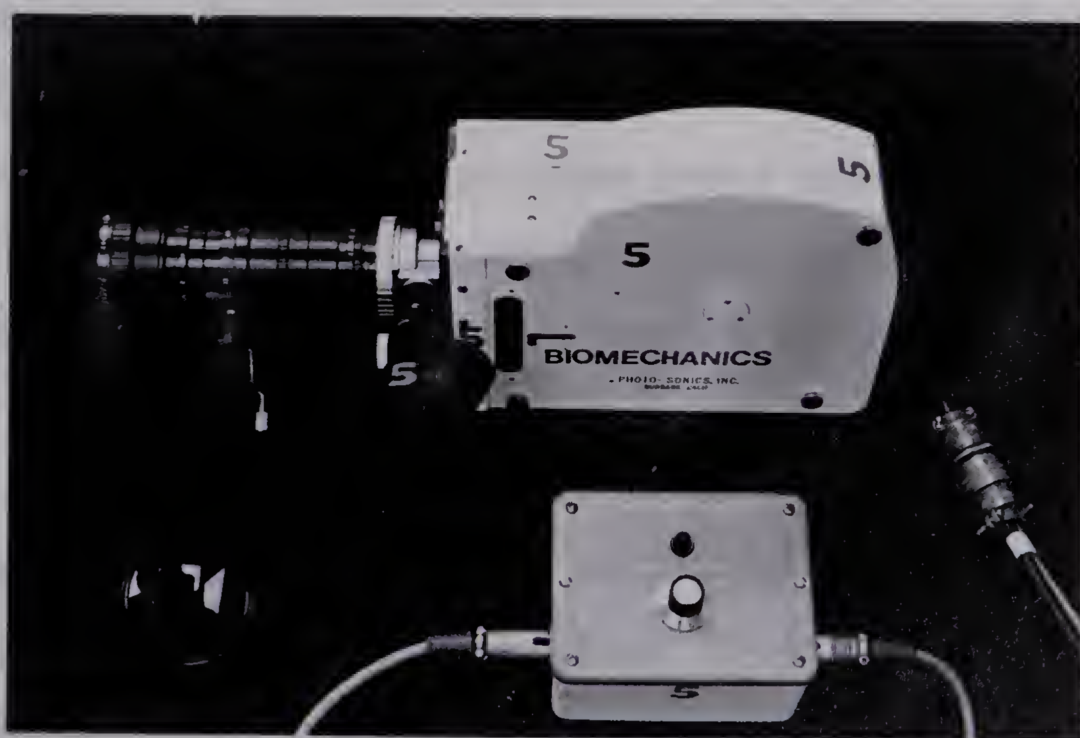


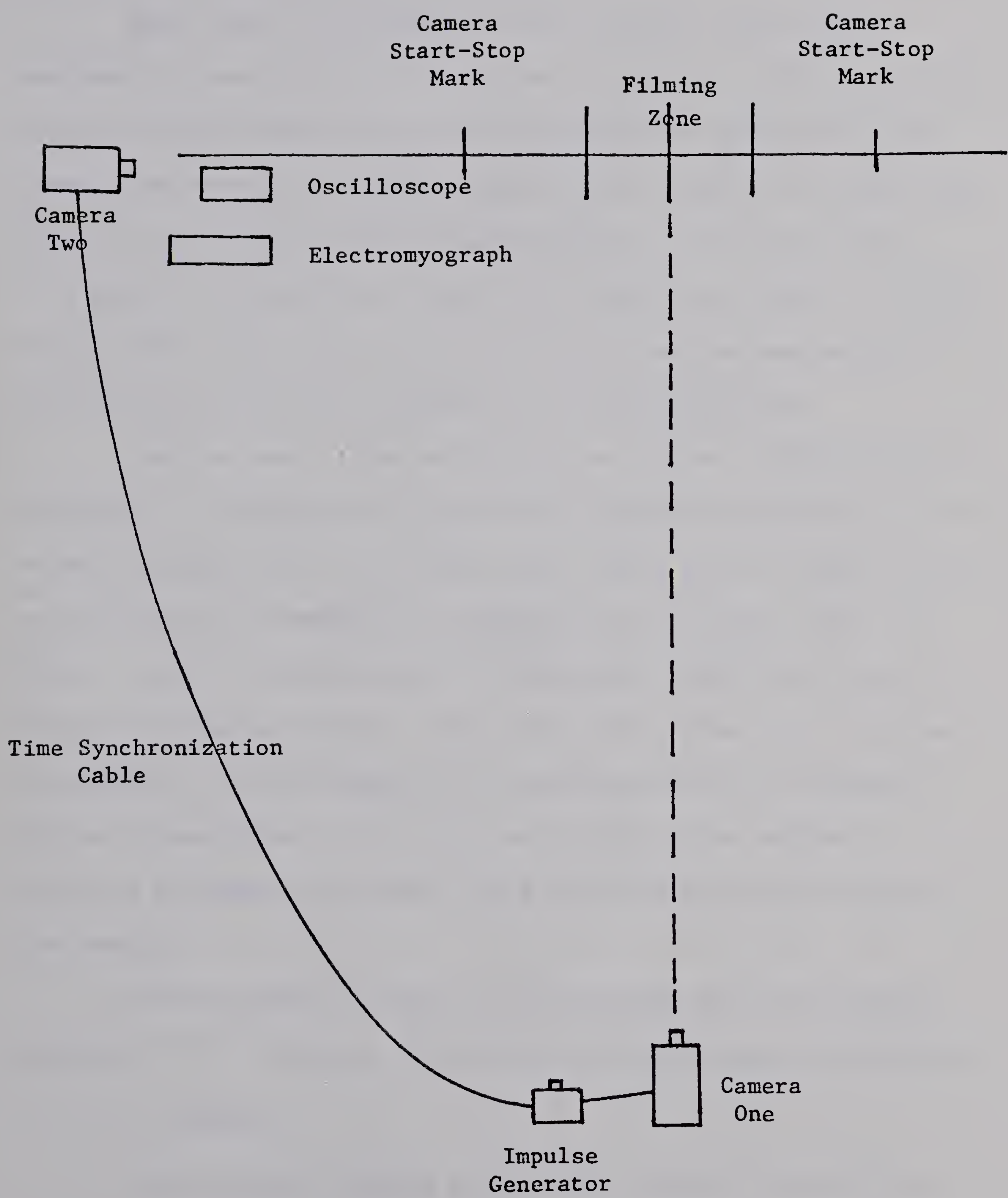
Figure 9. Cinematographical apparatus: Photo-Sonics camera with zoom lens, impulse generator and split lens.

disc electrodes two centimeters in diameter and having a one centimeter diameter cup were utilized to detect electrical activity. The paired bipolar surface electrodes were located and spaced longitudinally over the belly of each muscle near the respective motor point (20) such that minimal electrical overflow from near-by muscles was recorded when these muscles were contracted. Electrode position and overflow pick-up were examined through manual muscle testing procedures (25). The two ground electrodes were placed over near-by bony areas to ensure their relative electrical inactivity.

2. Cinematographic Recording System

The subject was photographed simultaneously by two synchronized Photo-Sonics 1 PL 16 mm movie cameras placed orthogonally. Camera One photographed the subject's lateral aspect as he walked toward or away from Camera Two (Figure 10). The lens of Camera Two was equipped with a split lens designed to permit simultaneous sharp focus of both the oscilloscope screen and the subject (Figure 9). The split lens combined a regular filter with a half-section close-up lens to permit single frame composition of near (oscilloscope) and far (subject) objects. The front half-section of the split lens rotated so that the near-by oscilloscope viewed through the close-up portion of the split lens, could be set at any selected position, e.g. to either side, top or bottom of the field of view.

The oscilloscope screen was placed facing Camera Two and to the right side of the camera's field of view. After focusing sharply on the subject, standing in the center of the filming zone, through the regular portion of the split lens the oscilloscope was moved towards or away from the camera lens until the oscilloscope light



Distances To Center of Filming Zone

Camera One - 29 m

Camera Two - 12 m

Figure 10. Schematic illustration of filming protocol. The subject's path of progression was along the volleyball court boundary.

traces were in sharp focus.

Each camera was equipped with two internal timing lights designed to leave light traces along each edge of the double perforated film. The Photo-Sonics Timing Pulse Generator was connected to both cameras and manually alternated between 10 Hz and 100 Hz, so that light traces could be made to appear simultaneously on the edges of both film records at frequencies of ten or one hundred per second. In this manner camera speed could later be calculated and synchronization of both films was possible by matching the timing light marks.

The time base of the oscilloscope was set at 1 millisecond per centimeter. Both cameras were previously calibrated under load at 58 fps using a Strobotac Type 1531 Timing Light, camera shutter angles were set at 160 degrees and exposure time calculated to be 1/130th second per frame. A spirit level was used to horizontally orient both cameras and the oscilloscope screen. Both cameras were fitted with 12-120 mm zoom lenses, f 2.8-22 (Angénieux, 72 mm diameter) set at a height of 100 cm, corresponding to the approximate height of the subject's center of mass. Kodak Ektachrome 7250 indoor film ASA 400 was used in both cameras.

The term center of mass (C of M) replaces the term center of gravity (C of G) throughout the remainder of the present investigation.

3. Subject

A male athlete, amateur soccer player, who was considered by the investigator to be in excellent physical condition and who had no history of significant lower extremity injury served as the subject.

At the time of final filming the subject's weight was 72.6 kg, height 180.0 cm and age 28.4 years.

The subject had been familiarized with the task of walking backwards over a four week period during which he practiced walking backwards at a free or comfortable speed five to seven steps in sequence, for approximately five minutes per day. His gait was examined by the investigator once per week during this time period. The subject was familiarized with the testing situation and equipment through pilot filming carried out three weeks prior to final filming. He was further familiarized with the EMG apparatus through six practice sessions held during these three weeks. At these times the EMG system was completely operative and the subject walked about, forwards and backwards, in order to become accustomed to the equipment.

III. TESTING PROCEDURE

Final filming was carried out at the University of Alberta Physical Education Building, West Gymnasium, in order to permit ready access to electrical outlets for the flood lights, the oscilloscope and and EMG. Pilot filming had been carried out three weeks prior to final filming in order to familiarize the subject with the apparatus and to assist in standardizing the experimental procedure. The subject had not played soccer within two days of either filming session.

White adhesive markers 4 cm square were attached over the joint centers of the subject's extremities (79,104) so as to be visable from Camera One. The subject wore his own running shoes, the soles and edges of which had been covered with white tape to contrast sharply with the walking surface.

The subject's skin at the point of electrode placement was first shaved. It was then cleansed with ethanol, dried and lightly abraided with sandpaper to remove the horny, dehydrated epidermis. A gauze pad was used to massage Parker 360 Electrode Paste into the designated area for a period of thirty seconds. Excess paste was wiped off to prevent formation of an electrical bridge between electrodes and to prevent electrode slippage, which could cause artifacts in the electromyogram. The disc electrodes were secured to the subject via Hewlett Parkard Two Sided Electrode Adhesive Discs and elastoplast tape.

Specific manual muscle testing procedures (25) were utilized to verify electrode positioning over the desired muscles. Each of the four EMG channels was adjusted so that an oscilloscope tracing of approximately one centimeter peak amplitude was avilable when the subject practiced backward walking, prior to actual testing. In this way the four oscilloscope beams, which were positioned two centimeters apart, interfered with one another minimally and still provided a satisfactory image for later analysis. All electrode pairs were placed approximately two centimeters apart over the respective muscle belly, but were moved closer together and/or repositioned if necessary to minimize overflow pick-up from adjacent muscle groups when these contracted.

To ensure that wire sway was minimal a thin light-weight, stretchy, polyurethane foam rubber bandage (7.5 cm wide) was wrapped around the left leg and over the electrodes and shielded electrode wires. This was completed in such a manner that joint centers were not obscured and complete freedom of hip, knee and ankle motion was

retained.

The subject was then allowed to walk freely about the gym, backwards and forwards, to become accustomed to the feel of the belt, pre-amplifier and electrodes. If he reported any hindrance to his normal gait patterns or a feeling that the belt was not adequately secure, adjustments were made and the subject allowed to resume walking. Such adjustments were made until the subject reported that he felt no gait abnormalities resulted.

The individual common mode balancing unit available to each channel and located on the remote transponder unit was utilized to balance input from each electrode of a pair. By viewing the oscilloscope electromyograms and/or listening to the audio electromyogram over headphones it was readily possible to balance the input from each electrode in a pair. The balance point was defined to be that point at which oscilloscope artifact and audio hum were minimal. Owing to the low level of electromagnetic interference at the time of final filming the 60 Hz notch filters, built into the amplifier unit, were used during only one trial, for comparison purposes only.

Camera One was positioned such that the optical axis of the lens horizontally bisected the middle of the filming zone. Camera Two was positioned along the path of progression and its lens adjusted such that the subject standing in the center of the filming zone was in sharp focus through the regular filter portion of the split lens. The oscilloscope and data card, which was attached to its face just below the screen, were moved toward or away from Camera Two until they were both in sharp focus through the close-up portion of the split lens. In this way the film taken by Camera Two was divided

such that the right half contained the oscilloscope and data card, while the left half carried the image of the subject as he moved toward or away from Camera Two. A 250 watt light was directed at the oscilloscope from behind the camera and positioned so that light meter readings off the data card and from the subject's thighs were similar.

Eight photographic lights of 750 watts each and two 1,000 watt lights were positioned such that Camera One filmed at an f-stop of 6 with a 70 mm lens setting. The film in Camera Two was pushed two times during development in order to permit filming at an f-stop of 11 with a 20 mm lens setting. Pushing the film was carried out in order to increase Camera Two's depth of field. An Aschi Pentax Spotmeter V was used to complete light meter readings and to guide final camera adjustments.

The subject walked backwards and forwards using a line painted on the floor, volleyball court boundary, as a reference line (Figure 10). He was not asked to walk along this line, but only to use it for guidance. Prior to each filming sequence a resting EMG in the standing position was recorded to use as an index of electrical activity. The subject walked approximately three meters before entering the filming zone, continued walking through the zone and two meters past the zone. Strips of reflective white tape one meter in length, which were placed perpendicular to the guidance line and positioned one meter apart, provided reference scale markers. As well, horizontal and vertical range poles, one meter in length, with their axis at a height of one meter, were filmed at the start, middle and end of the filming zone by both cameras at the termination of final filming.

Since there were only four EMG channels available at one time it was necessary to reposition the electrodes over a different group of muscles for each sequence. Only the left lower extremity was examined. The following muscle groups were examined:

Sequence No. 1	Sequence No. 2	Sequence No. 3
1. Rectus Femoris	1. Medial Head Gastrocnemius	1. Gluteus Maximus
2. Medial Hamstrings	2. Peroneus Longus	2. Total Hamstrings
3. Lateral Hamstrings	3. Tibialis Anterior	3. Gluteus Medius
4. Vastus Lateralis	4. Vastus Medialis	4. Adductor Longus

Six trips, or walk pasts, were recorded for each electrode positioning sequence, three trips forward and three trips backward. Beginning at the backward subject start mark the subject walked backwards, away from Camera Two, through the filming zone and beyond it. He then positioned himself on the forward subject start mark and walked forward toward Camera Two, through the filming zone and beyond it. In this manner backward and forward walking trips were alternated. The first trial was defined to include the first backward and the first forward walking trips. The second trial included the second trips and the third trial included the third trips.

IV. DATA ANALYSIS

Two synchronized 16 mm film records illustrating the subject's gait from anterior and lateral views were available. Film Two also contained the EMG record. The developed films were first matched according to sequence number and trial number. The interval timing light marks located along the edges of both films were used to provide a precise frame-for-frame match-up of Film One and Film Two. Each trial was then spliced out of the copy films, marked and placed

in a separate canister so that both the lateral and the anterior views were available, together. Each frame of Film One was numbered and the matching frame on Film Two was identically numbered.

The timing light marks were used to determine actual camera speed. The Triad-V/R-100 Motion Picture Analyser was utilized to determine the points of occurrence of specific events, such as heel-strike, foot-flat and toe-off, first in the forward walking sequences and later in the backward walking sequences. The backward walking trials were reviewed with the intent of locating specific events which could correspond with events observed during the forward walking cycle and the backward walking cycle sub-divided accordingly.

Film One, the lateral view, was projected onto a Bendix Digitizer Board (accuracy $\pm$ 0.001 inch) and an alignment program was utilized to horizontally orient the floor, in the projected film, parallel to the X-axis of the digitizer board, for the first frame of film. A Bendix Cursor was utilized to enter first the coordinates of a standard reference point, which became the origin, and then, in constant order, the twenty-eight reference points into a Hewlett-Packard 9825A Calculator. A program stored on magnetic tape was utilized to calculate the position of the top of the head and the location of the body C of M, with respect to the standard reference point. Humanscale Anatomical Data (26) on the relative masses of the body segments and the location of the segmental C of M's was utilized in the computer program. All frames of film analysed were approached with the film projector moving in one direction, forward, so as to minimize film slippage owing to changes in direction. Vertical displacements were later transposed to a scale such that the initial

floor strike position of the body C of M and the top of the head became zero reference points.

The joint angles of the left hip, knee and ankle were also determined from Film One using the HP 9825A and another stored program, based on the cosine law. Joint angles were later transferred to scales based on the joint angle nomenclature proposed by the American Academy of Orthopaedic Surgeons (48).

Film Two was examined using the Triad-V/R-100 Motion Picture Analyser. The initial floor-strike position was utilized as the zero reference point and the coordinates of the lateralmost point on the left hip were determined with respect to this point. Because the subject did not walk perfectly along the guidance line, toward or away from Camera Two, the initial floor-strike coordinates did not match the final floor-strike coordinates. That is, the subject's line of progression was generally diagonal to the guidance line, not parallel to it. To compensate for this divergence the lateral displacements were calculated as the perpendicular distance from the hip coordinates in a specific frame of interest to the line joining the initial and the final floor-strike coordinates, at the start and the end of the walking cycle.

CHAPTER FOUR

RESULTS

I. INTRODUCTION

The two cameras had been calibrated and synchronized under load. Matching Film One and Film Two on a frame-to-frame basis was a simple and convenient procedure because the two cameras ran near a frame-for-frame speed. All measurements from the film were taken by this author in order to avoid inter-individual differences in measurement.

II. TERMINOLOGY

The initial task was the division of the backward walking cycle into specific events which could act as the boundaries for component phases and sub-phases. Film One was intensively reviewed and the backward walking cycle examined in light of the specific events and component sub-phases of the forward walking cycle. On this basis the backward walking cycle was sub-divided as follows (see Figures 11 and 12 and Tables III and IV):

Stance Phase was that period during which the foot was in contact with the ground. It began at the instant that the toe struck the ground (toe-strike) and ended at the instant that ground contact was broken with that foot (heel-off). The limb then swung backward toward the next toe-strike.

Swing Phase was that period during which the foot was off the ground moving backward toward the next toe-strike. It began at the instant that ground contact was broken (heel-off) and ended at the instant that ground contact was again made with that foot (toe-strike).

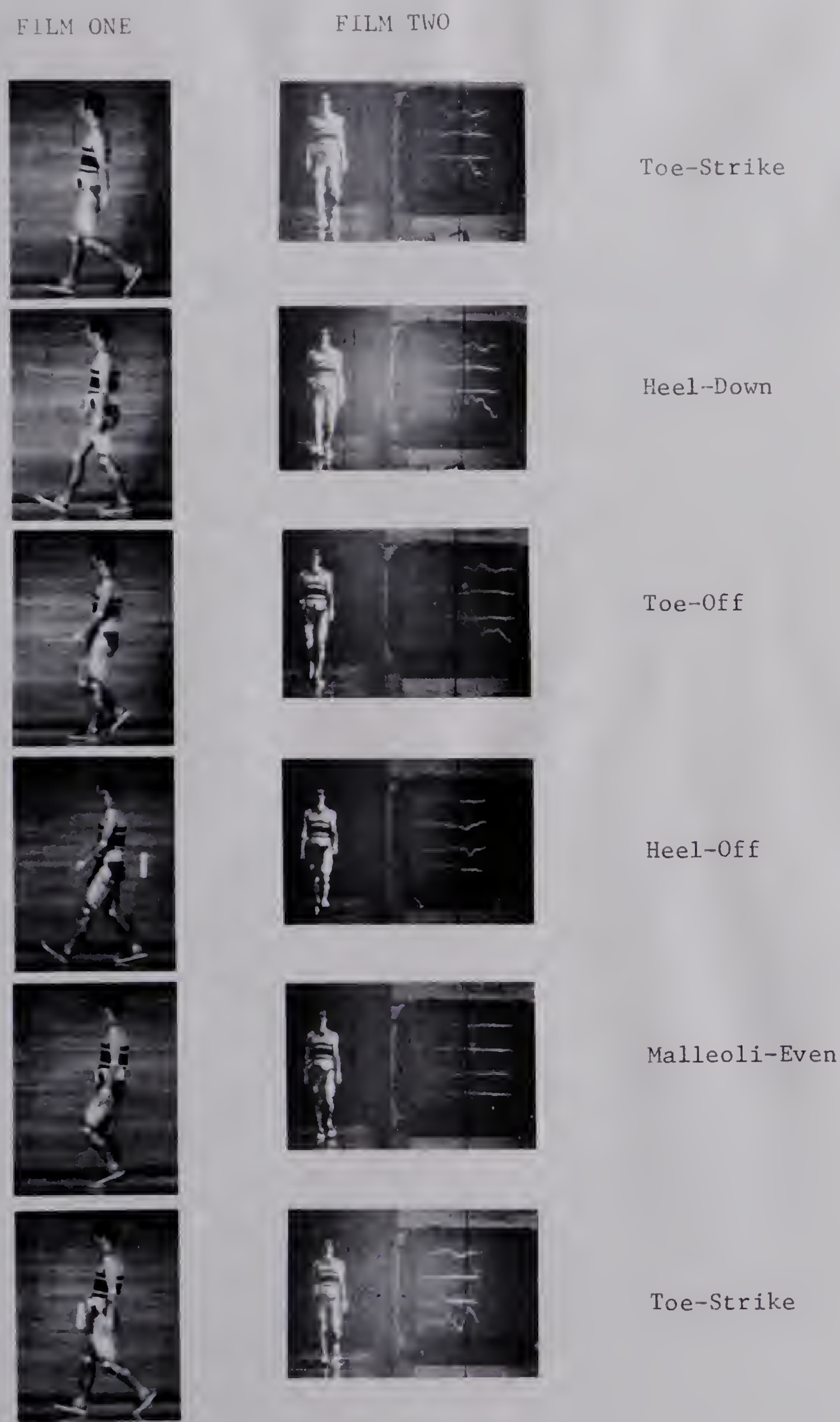


Figure 11. Specific events of the backward walking cycle, left lower extremity, and the simultaneous electromyograms (top to bottom of oscilloscope screen: rectus femoris, medial hamstrings, lateral hamstrings and vastus lateralis).

Figure 12. Graphic illustration of events, phases and sub-phases during backward and forward walking cycles (means of nine walking cycles).

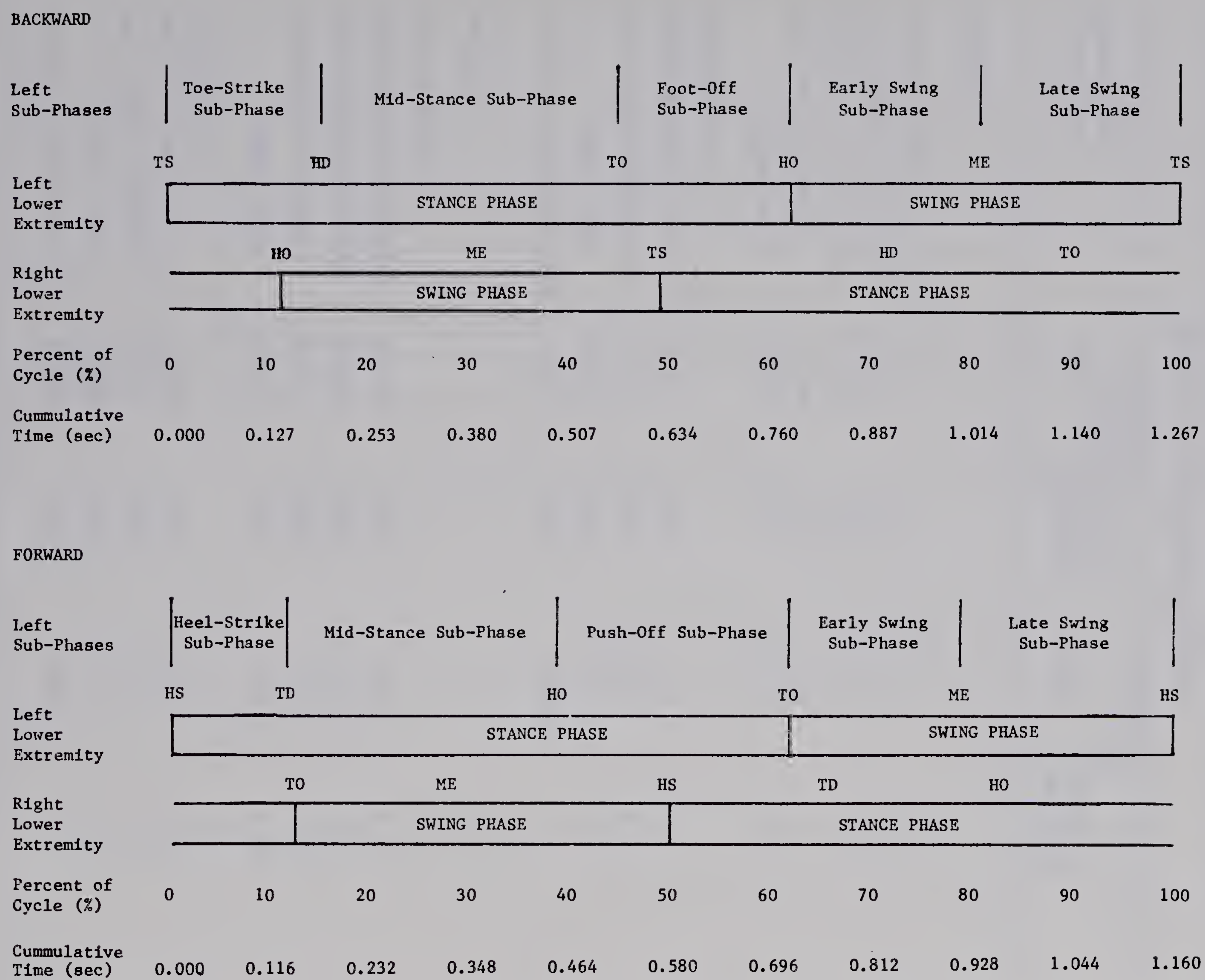

BACKWARD
Left Sub-Phases
Toe-Strike Sub-Phase
Mid-Stance Sub-Phase
Foot-Off Sub-Phase
Early Swing Sub-Phase
Late Swing Sub-Phase
TS HD TO HO ME TS
Left Lower Extremity
STANCE PHASE
SWING PHASE
HO ME TS HD TO
Right Lower Extremity
SWING PHASE
STANCE PHASE
Percent of Cycle (%)
0 10 20 30 40 50 60 70 80 90 100
Cummulative Time (sec)
0.000 0.127 0.253 0.380 0.507 0.634 0.760 0.887 1.014 1.140 1.267
FORWARD
Left Sub-Phases
Heel-Strike Sub-Phase
Mid-Stance Sub-Phase
Push-Off Sub-Phase
Early Swing Sub-Phase
Late Swing Sub-Phase
HS TD HO TO ME HS
Left Lower Extremity
STANCE PHASE
SWING PHASE
TO ME HS TD HO
Right Lower Extremity
SWING PHASE
STANCE PHASE
Percent of Cycle (%)
0 10 20 30 40 50 60 70 80 90 100
Cummulative Time (sec)
0.000 0.116 0.232 0.348 0.464 0.580 0.696 0.812 0.928 1.044 1.160

TABLE III

Duration of Phases and Sub-Phases During Backward and Forward Walking Cycles

(means of nine walking cycles)

Phases and Sub-phases	Duration (sec) Mean	Standard Deviation	Percent of Cycle (%) Mean	Standard Deviation
BACKWARD				
Stance Phase				
Toe-Strike Sub-Phase	0.197	0.025	15.5	1.9
Mid-Stance Sub-Phase	0.382	0.036	30.2	3.1
Foot-Off Sub-Phase	0.208	0.031	16.4	2.2
Phase Total	0.788	0.021	62.1	0.7
Swing Phase				
Early Swing Sub-Phase	0.245	0.021	19.3	1.5
Late Swing Sub-Phase	0.235	0.017	18.6	1.2
Phase Total	0.480	0.016	37.9	0.7
Walking Cycle Duration	1.267	0.032	100.00	
FORWARD				
Stance Phase				
Heel-Strike Sub-Phase	0.138	0.017	11.9	1.4
Mid-Stance Sub-Phase	0.319	0.030	27.5	2.8
Push-Off Sub-Phase	0.277	0.044	23.9	3.6
Phase Total	0.734	0.015	63.3	0.8
Swing Phase				
Early Swing Sub-Phase	0.182	0.009	15.7	0.8
Late Swing Sub-Phase	0.245	0.008	21.1	0.7
Phase Total	0.426	0.008	36.8	0.8
Walking Cycle Duration	1.160	0.013	100.0	

TABLE IV

Values of Selected Parameters of The Backward and Forward Walking Cycles

(means of nine walking cycles)

Parameter	BACKWARD		FORWARD	
	Mean	Standard Deviation	Mean	Standard Deviation
Cadence (steps/min)	94.76	2.34	103.46	1.12
(strides/min)	47.38	1.17	51.73	0.56
Stride Length (cm)	145.30	4.05	161.76	3.64
Step Length (cm)				
-Right	73.33	3.12	81.57	1.88
-Left	71.97	2.49	80.19	2.37
Horizontal Velocity (cm/sec) Measured At:				
-Top of Head	115.39	3.90	137.44	2.94
-Body C of M	113.88	4.03	138.18	2.09
-Left Foot	114.72	3.87	139.45	3.28
Double Limb Support Duration (sec)				
-First Period	0.153	0.010	0.157	0.010
-Second Period	0.161	0.015	0.141	0.012
-Both Periods Combined	0.313	0.021	0.298	0.017
Step Length Expressed As A Percentage of Stride Length				
-Right	50.5	1.3	50.4	0.7
-Left	49.5	1.3	49.6	0.7
Double Limb Support Period(s) Expressed As A Percent of Walking Cycle Duration				
-First Period	12.1	0.6	13.5	0.8
-Second Period	12.7	1.1	12.2	1.0
-Both Periods Combined	24.7	1.3	25.7	1.3

The following specific events were used to assign boundaries to the component phases and sub-phases of the backward walking cycle:

1. Toe-Strike - the instant at which the toe of the previously swinging leg contacted the ground

2. Heel-Down - the instant at which the heel of the foot made contact with the ground, the toes of the foot also being in ground contact.

3. Malleoli-Even - the instant at which the medial malleoli of the swinging and the stance legs lay in the same plane, which was the subject's frontal plane, or a plane parallel to it

4. Toe-Off - the instant at which the toe broke contact with the ground, the heel of the foot remaining in ground contact

5. Heel-Off - the instant at which the heel broke contact with the ground.

Sub-Phases of Stance Phase were defined as follows:

1. Toe-Strike Sub-Phase - began at toe-strike and ended at heel-down

2. Mid-Stance Sub-Phase - began at heel-down and ended at toe-off. It was a period of single limb support, with the entire sole of the stance foot in ground contact

3. Foot-Off Sub-Phase - began at toe-off and ended at heel-off.

Sub-Phases of Swing Phase were defined as follows:

1. Early Swing Sub-Phase - that period during which the backward swinging leg began to travel backward through space (heel-off) and caught up to the stance leg (malleoli-even)

2. Late Swing Sub-Phase - that period during which the backward swinging leg moved from a position of malleoli-even to ground contact (toe-strike) behind the body.

III. SELECTED TEMPORAL AND SPATIAL PARAMETERS

The backward walking cycle was defined to extend from toe-strike of one foot until the next toe-strike of the same foot. It encompassed two steps, one left and one right, and was equivalent to one complete stride of the lower extremity under examination. Tables III and IV and Figure 12 illustrate temporal and spatial aspects of both the backward and the forward walking cycles.

Double limb support periods were defined to consist of those periods during which both feet were simultaneously in contact with the ground. Two separate periods of double limb support were observed as the stance and the swing phases of both legs overlapped, in both backward and forward walking.

IV. DISPLACEMENT OF THE BODY CENTER OF MASS AND THE HIP

During each walking cycle the body center of mass (C of M) and the top of the head oscillated through two vertical high points, during mid-stance of opposite legs, and two vertical low points, during double limb support periods (Figure 13 and Table V).

At the same time the left hip oscillated about the line of progression, reaching its peak displacements during mid-stance of alternate legs. Figure 14 and Table VI describe the path of the lateralmost point on the left hip during single backward and forward walking cycles, as viewed from a position anterior to the subject.

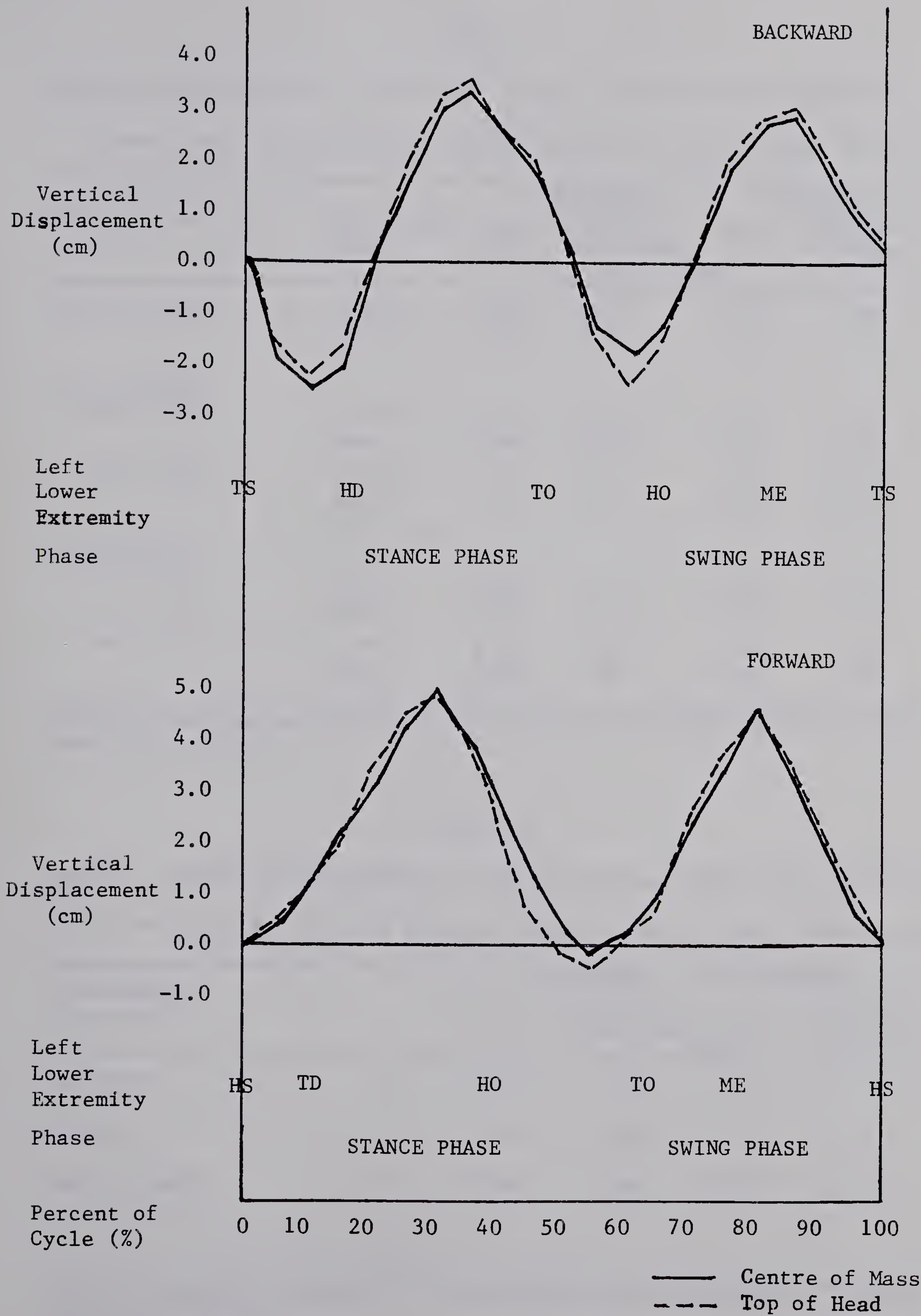


Figure 13. Vertical displacements at specific percentages of the backward and forward walking cycles (means of nine walking cycles). Data listed in Tables IX and XI of Appendix A.

TABLE V

Vertical Displacements of The Body Center of Mass and The Head During Backward and Forward Walking Cycles (means of nine walking cycles)

Displacement (cm)	Measurement Point	BACKWARD Mean	BACKWARD Standard Deviation	FORWARD Mean	FORWARD Standard Deviation
			(cm)		
Peak-to-Peak	C of M	6.13	0.77	5.29	0.58
	Head	6.60	0.57	5.37	0.49
Stance Phase					
-Low Point	C of M	-2.63	0.79	-0.21	0.21
	Head	-2.41	1.06	-0.41	0.26
-High Point	C of M	3.34	0.33	4.85	0.63
	Head	3.79	0.60	4.85	0.52
Swing Phase					
-Low Point	C of M	-2.09	0.97	0.10	0.27
	Head	-2.58	1.01	-0.01	0.27
-High Point	C of M	2.82	0.65	4.42	0.38
	Head	3.04	0.49	4.42	0.52

The zero position was taken as the position at the instant of initial foot-floor contact.

TABLE VI

Lateral - Medial Displacements of The Lateralmost Point On The Left Hip During Backward and Forward Walking Cycles (means of nine walking cycles)

Displacement Direction	BACKWARD Mean	BACKWARD Standard Deviation	FORWARD Mean	FORWARD Standard Deviation
		(cm)		
Laterally	3.16	0.46	3.44	0.63
Medially	2.12	0.41	1.72	0.31
Peak-to-Peak	5.28	0.60	5.17	0.79

The zero position was taken as the position at the instant of initial foot-floor contact.

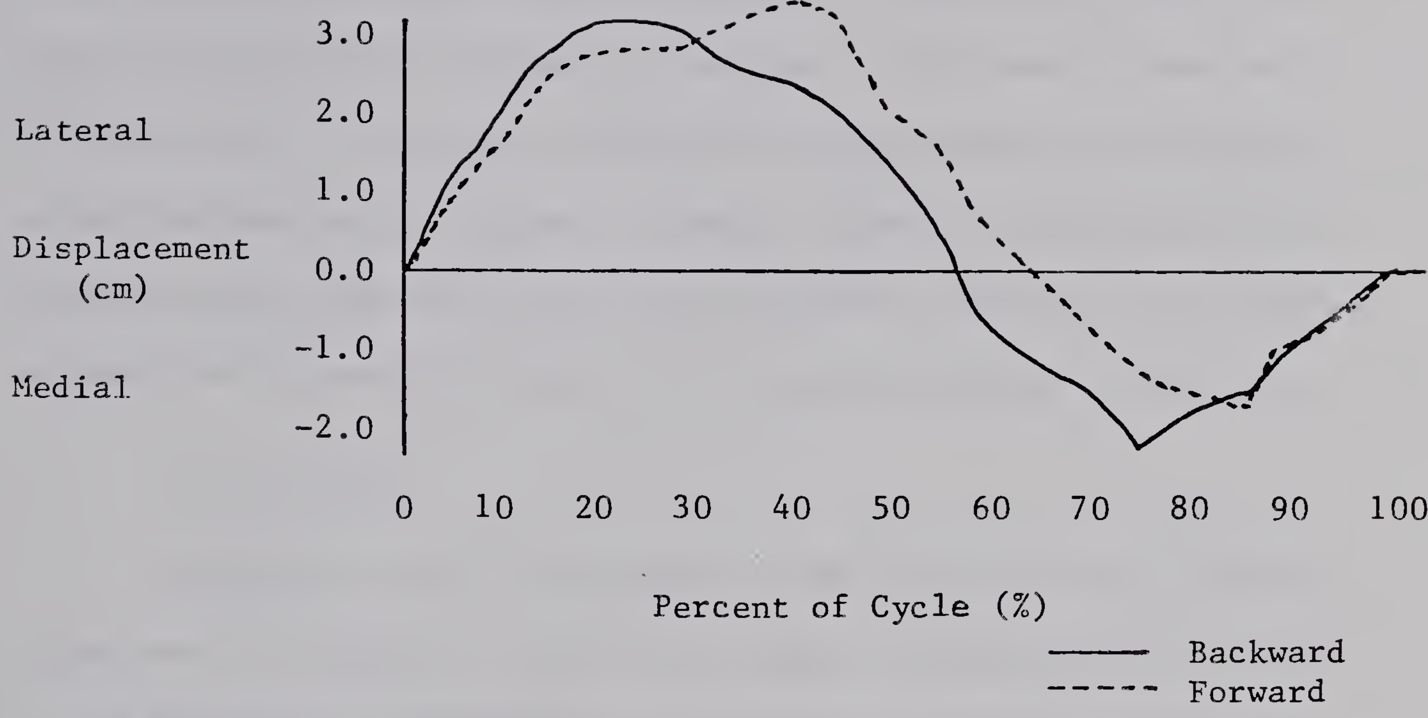


Figure 14. Lateral - Medial displacements of the left hip during backward and forward walking cycles (means of nine walking cycles).

TABLE VII

Mean Horizontal Displacements and Mean Horizontal Velocities During Ascent and Descent of The Trunk As Measured At The Body Center of Mass During Backward and Forward Walking

Ascent or Descent	Backward				Forward			
	Displacement		Velocity		Displacement		Velocity	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Ascent	7.04	0.65	111.16	10.27	7.94	1.06	136.98	18.27
Descent	7.40	0.86	116.78	13.51	8.10	0.81	139.71	13.88
Overall	7.22	0.76	113.97	12.03	8.01	0.93	138.21	16.08

Horizontal displacements expressed as cm/5% division of the walking cycle.
Horizontal velocities expressed as cm/sec.

Horizontal displacements (cm/5% division of the walking cycle) and horizontal velocities (cm/sec) of the body C of M were determined for both gaits. Throughout, horizontal displacements and horizontal velocities demonstrated erratic changes. However, horizontal displacements and horizontal velocities decreased slightly as the trunk ascended and increased slightly as the trunk descended (Table VII).

V. JOINT ANGLES

The excursions of the joints of the left lower extremity are illustrated in Figure 15. All joint angles are expressed according to the nomenclature suggested by the American Academy of Orthopedic Surgeons (48). The maximum angles observed at each joint were as follows:

Hip	Backward	10° extension and 25° flexion
	Forward	16° extension and 26° flexion
Knee	Backward	-2° extension and 67° flexion
	Forward	-3° extension and 71° flexion
Ankle	Backward	22° dorsiflexion and 6° plantarflexion
	Forward	12° dorsiflexion and 16° plantarflexion

VI. ELECTROMYOGRAPHIC SEQUENCE OF ACTIVITY

At the time of final filming, early Sunday morning, there appeared to be a relatively low level of electromagnetic interference. This low level of atmospheric interference, combined with meticulous care in attaching individual electrodes, made it unnecessary to utilize the 60 Hz notch filters in order to obtain a flat, resting EMG baseline.

Film One and Film Two were first matched frame-for-frame on the basis of the interval timing light marks along the edges of both films.

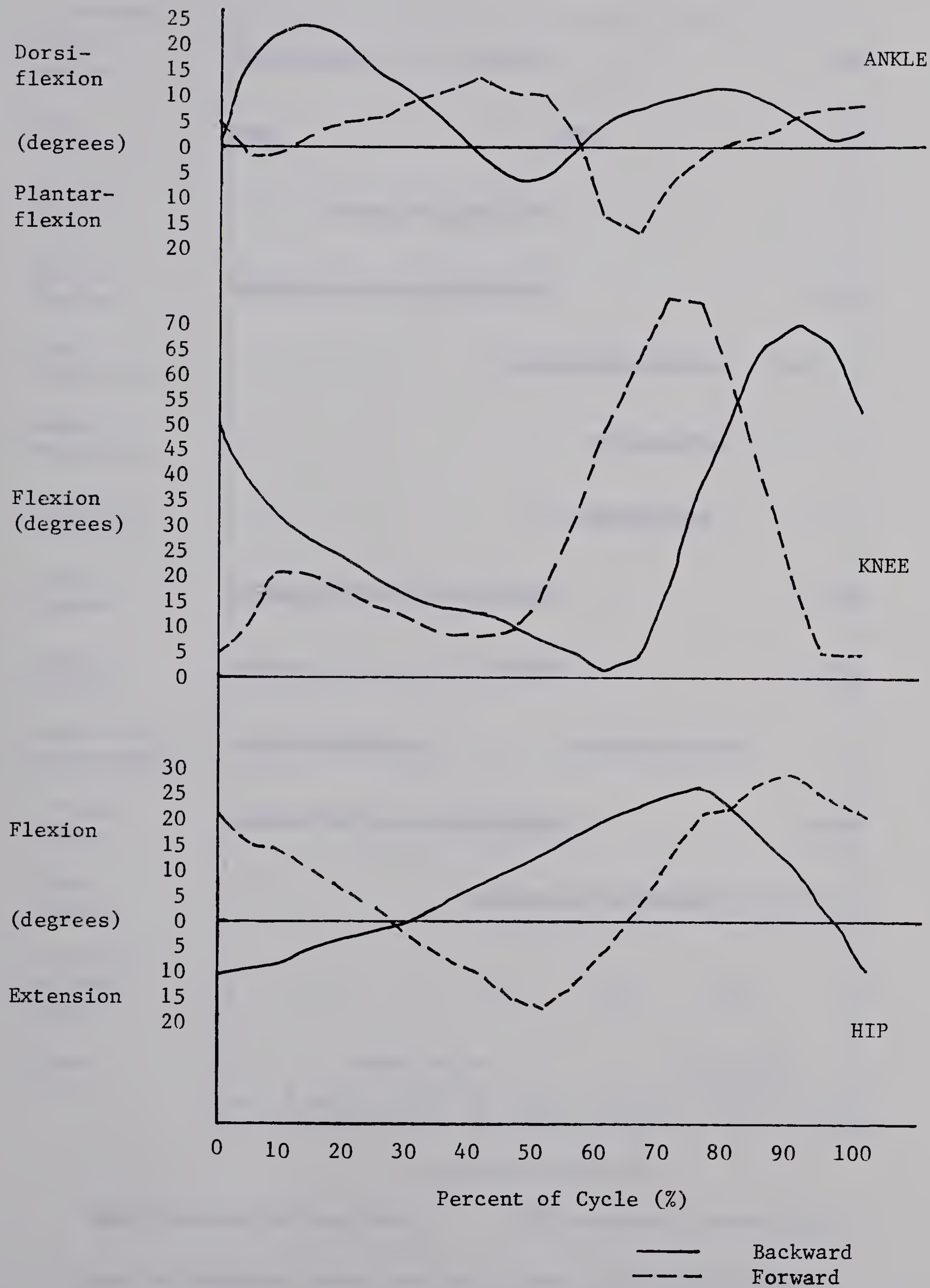


Figure 15. Excursions of the joints of the left lower extremity during backward and forward walking cycles (means of nine cycles).

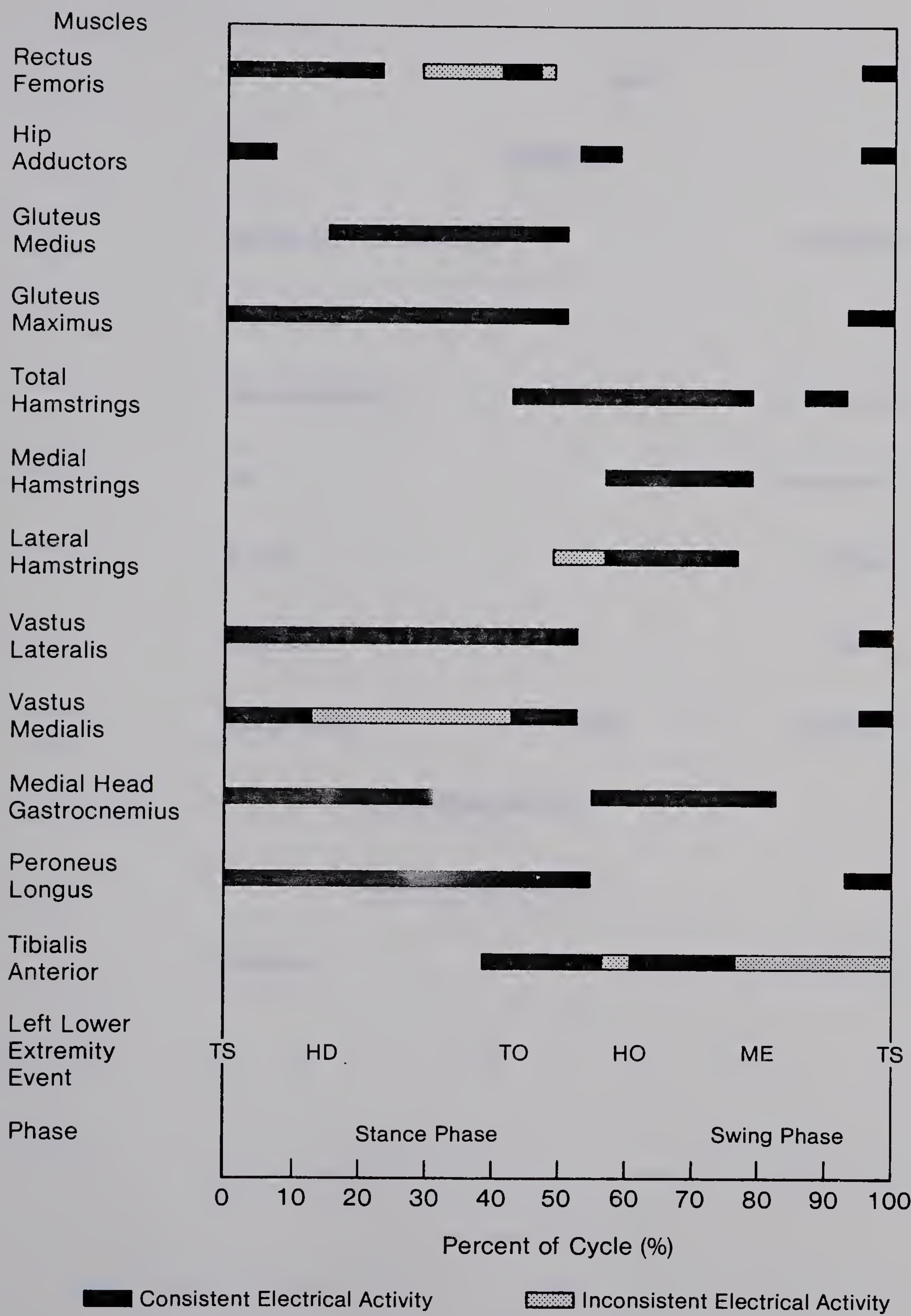


Figure 16. Electromyographical sequence of activity during backward walking (means of three walking cycles), expressed as percent activity duration of the walking cycle.

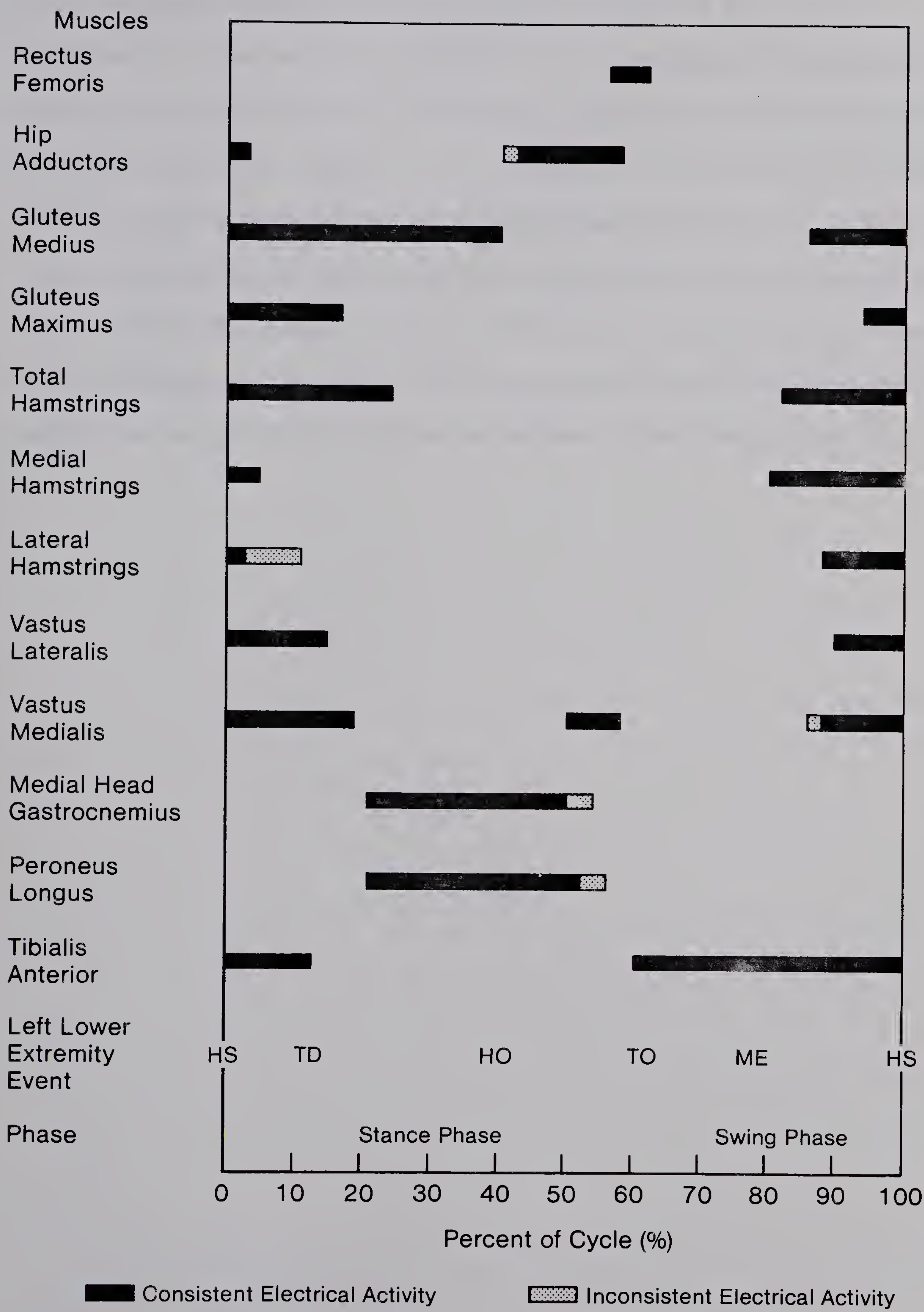


Figure 17. Electromyographical sequence of activity during forward walking (means of three walking cycles), expressed as percent activity duration of the walking cycle.

Each individual frame of Film Two, which carried the EMG record, was examined. Muscles were considered to be consistently electrically active at a specific time if the degree of electrical activity during all three cycles was judged to be at least 25% that observed at maximal intensity during each particular stride (Figures 16 and 17). Muscles were considered to be inconsistently electrically active if one of the three strides was judged to be not active, but the other two strides were considered to be active. Muscles demonstrating electrical activity during one, or none of the three trials were classified as not active.

CHAPTER FIVE

DISCUSSION

I. INTRODUCTION

The use of two synchronized cameras and an impulse generator to simultaneously activate the timing lights within each camera proved to be a satisfactory means of recording both EMG and subject activity, and permitting synchronization of the two films. By combining EMG and subject activity on Film Two the need for a separate EMG record was eliminated.

The present investigation relied on visual detection of specific events to assign the boundaries to the walking cycle, and its component phases and sub-phases. The only point of difficulty in establishing foot-surface contact instances was the precise determination of heel-off during backward walking. The subject tended to lift the heel vertically very little and the first indication of heel-off was often backward movement of the heel. Sutherland et al. (91) were the only investigators to comment on the use of visual versus electronic indicator determination of heel-strike and toe-off during forward walking. No significant differences between the two methods were observed in subjects with normal feet. The statistical procedure utilized was not specified.

II. TERMINOLOGY

Corresponding terms have been utilized to describe the component phases, sub-phases and specific events of the backward and forward walking cycles. The point of division between early and late swing sub-phases was selected to be malleoli-even, the instant at which the

medial malleolus of the swinging leg and the medial malleolus of the stance leg lay in the same plane, the frontal plane or a plane parallel to it. This point can be readily approximated by the naked eye and can be applied to both the backward and the forward walking cycles. As well, it specifies an instant in time, whereas the term mid-swing is less definitive and has generally been used as a swing phase sub-phase.

The corresponding events and sub-phases utilized in the present investigation are outlined below:

	Corresponding Events			Corresponding Sub-Phases	
	Backward	Forward		Backward	Forward
1.	Toe-Strike	Heel-Strike	1.	Toe-Strike	Heel-Strike
2.	Heel-Down	Toe-Down	2.	Mid-Stance	Mid-Stance
3.	Malleoli-Even	Malleoli-Even	3.	Foot-Off	Push-Off
4.	Toe-Off	Heel-Off	4.	Early Swing	Early Swing
5.	Heel-Off	Toe-Off	5.	Late Swing	Late Swing

Perry (78) outlined a relatively new gait terminology designed for use with both normal and abnormal forward gaits. The more traditional terms were retained in the present investigation because they are both functionally meaningful and they can readily be made use of in the clinical situation, where it is necessary to work with non technically trained individuals, including patients. However, Perry's nomenclature will be considered here because it is the first nomenclature that is adaptable to abnormal gait. In such cases it is not feasible to use an anatomically based nomenclature because the individual may make floor contact with only part of the foot and/or may have an incomplete swing phase. The terminology outlined in the present investigation is designed for normal gait and use in non

technical situations. Perry's terminology is compared to that utilized in the present investigation, for backward walking, below:

Perry (78)		Present Investigation
1. Initial Contact	STANCE PHASE	Toe-Strike
2. Loading Response	STANCE PHASE	Heel-Down
3. Mid-Stance	STANCE PHASE	No Corresponding Event
4. Terminal Stance	STANCE PHASE	Toe-Off
5. Pre-Swing	STANCE PHASE	Heel-Off
1. Initial Swing	SWING PHASE	Early Swing Sub-Phase
2. Mid-Swing Sub-Phase	SWING PHASE	No Corresponding Sub-Phase
3. Terminal Swing Sub-Phase	SWING PHASE	Late Swing Sub-Phase

III. SELECTED TEMPORAL AND SPATIAL PARAMETERS

Temporal and spatial parameters for the backward and forward walking cycles were reported in Chapter Four. Overall, the backward walking cycle was slower in terms of cadence and horizontal velocities (measured at the head, the body C of M and the left foot) and demonstrated shorter stride and step lengths. Within each gait the horizontal velocities measured at the top of the head, the body C of M and the left foot, varied little from one another. Left and right step lengths within each gait also differed little from one another, representing approximately 50% of the stride length in each case.

The temporal and spatial values observed in the present investigation are similar to those reported by Murray et al. (69), as listed in Table I. The major area of difference lies in the forward walking velocity, 151 $\pm$ 20 cm/sec reported by Murray et al. (69), as compared to 138 $\pm$ 2 cm/sec reported in the present investigation.

Despite the additional backward walking practice carried out specifically for this study, it is probable that the subject devoted considerably more time to forward walking than to backward walking during each day. During backward walking he could not see directly where he was going because he faced opposite to his direction of travel. Consequently, backward walking was guided more by proprioceptive information, and less by visual information, than was forward walking. Hip extension range of motion, being less than hip flexion range of motion, limited the extent to which the subject could step backwards. The slower walking cadence and horizontal velocity, and shorter stride and step lengths observed during backward walking may be largely attributable to these factors. As well, other studies have generally averaged values from several subjects to obtain a mean walking speed and have generally examined only one or a few trials per subject.

The mean seconds duration of the backward walking cycle, backward stance phase and backward swing phase was significantly greater than its forward counterpart. The mean proportion of the forward walking cycle spent in stance phase was significantly greater than the mean proportion of the backward walking cycle spent in stance phase. Similarily, the mean proportion of the backward walking cycle spent in swing phase was significantly greater than the mean proportion of the forward walking cycle spent in swing phase (Appendix C).

The duration (seconds and percent of the walking cycle) of double limb support period, both periods combined, did not differ significantly when backward and forward mean durations were compared. No significant difference was observed between the mean durations of the first and the second periods of double limb support during backward walking. However,

during forward walking the mean duration of the first period of double limb support was significantly greater than the mean duration of the second period of double limb support (Appendix C).

Within each gait the duration of mid-stance sub-phase (seconds and percent of the walking cycle) was significantly greater than the duration of any other sub-phase. During backward walking this sub-phase was entirely a period of single limb support with a much longer period of single limb support, for the left lower extremity. The mid-stance sub-phase portion of the right lower extremity forward walking cycle was a total single limb support period, owing to the reversal of toe-off and toe-down instants of occurrence.

Backward walking was characterized by similar periods of time (seconds and percent of the walking cycle) spent in the initial floor-contact sub-phase (Toe-Strike) and the pre-swing sub-phase (Foot-Off). Significantly greater and similar lengths of time were spent in each of the two backward swing sub-phases. During forward walking the smallest proportion of the walking cycle was spent in the initial floor contact sub-phase (Heel-Strike), while significantly greater time was spent in the pre-swing sub-phase (Push-Off). Late swing sub-phase was of significantly greater duration than was early swing sub-phase (Appendix C). The greater stride length and horizontal velocity observed during forward walking can be partially attributed to the extended push-off and late swing sub-phases observed during forward walking.

The order of occurrence of specific events was consistent throughout all trials of both gaits. However, the precise points of occurrence, percent of the walking cycle, of specific events varied slightly from trial to trial and from left leg to right leg, see Figure 12 and Table VIII. Since complete walking cycles for the right lower extremity were not examined, it is not possible to comment on right-left comparison of the pre-swing sub-phases, foot-off and push-off, during either gait.

During backward walking the sequence of specific events was the same for both legs, however, differences in the instants of occurrence of heel-down and toe-off altered right-left sub-phase durations slightly. In comparison to the left lower extremity, right heel-down was delayed, while right toe-off was early.

During forward walking the most obvious difference between the lower extremities was the reversed order of occurrence of toe-down and toe-off during the left and right walking cycles. The left foot reached toe-down, to complete its heel-strike sub-phase and initiate its mid-stance sub-phase, before the right foot had made toe-off to initiate right swing phase. Thus, the left heel-strike sub-phase was oneeof total double limb support and left mid-stance sub-phase encompassed a brief period of double limb support and a longer period of single limb support. The right foot did not reach toe-down, to complete its heel-strike sub-phase and initiate its mid-stance sub-phase, until after the left foot had made toe-off to initiate left swing phase. Consequently, right toe-strike sub-phase included a brief period of single limb support, but was predominantly a period of double limb support. Right mid-stance sub-phase was totally a period of single limb support.

During both gaits the subject spent more time in the initial stance sub-phase during the right lower extremity cycle, as compared to the left lower extremity cycle. He then spent less time in the right mid-stance sub-phase, during both gaits. Similar periods of time were spent in the left and right swing phase sub-phases during both gaits.

As previously stated, the order of occurrence of the specific events was consistent from trial to trial during both gaits. This indicates that the sequence of events observed represented the individual's normal gait pattern. Similar data describing the instants of occurrence of specific events, involving both lower extremities, was not located in the available literature. The uneveness of timing of some events observed in the present investigation is in probability an individual idiosyncrasy.

IV. DISPLACEMENTS OF THE BODY CENTER OF MASS AND THE HIP

1. Vertical Displacement of The Body Center of Mass

The vertical displacement curves of the body C of M and the top of the subject's head during normal backward and forward walking were low amplitude and sinusoidal in nature (Figure 13). However, the curves were neither identical nor perfectly sinusoidal. The zero position was taken as the position at the instant of foot-floor contact and the initiation of the walking cycle.

The backward walking curves demonstrated marked differences from the corresponding forward walking curves. The low points during backward walking occurred after toe-strike, just before contralateral heel-off and the termination of double limb support periods. The low

points during forward walking occurred near heel-strike, the beginning of double limb support periods. The high points during both gaits occurred shortly after the respective malleoli-even points, during mid-stance of alternate legs, near the middle of single limb support periods. The events of malleoli-even, left and right legs, did not correspond to the maximum vertical high displacements during either gait, although these occurred closely together. During backward walking the event of heel-off did not correspond to the maximum vertical low displacements. The paths of the head and the body C of M were already rising by heel-off.

Previous investigations have reported similar, although slightly lower, peak-to-peak vertical displacements during forward walking (30,54,55,68,70,71,85). In the present investigation vertical displacements during the backward walking cycle were characterized by lower vertical lows and lower vertical highs than the forward walking cycle. The mean vertical range, or peak-to-peak displacement during backward walking was significantly greater than the mean displacement during forward walking, measured at both the top of the head and the body C of M (Appendix C).

The present investigation took into consideration the influence of the various body segments on the body C of M and utilized the principle of moments to calculate the location of the body C of M in selected frames of film. The position of the top of the subject's head (distal head and neck) was also output by the same computer program. Comparison of the vertical paths of the top of the head and the calculated body C of M, as illustrated in Table IX of Appendix A and Figure 13, indicated only two instances of significant difference in thirty-eight separate

comparisons during both gaits (Appendix C).

The investigator was unable to locate a previous gait study which similarily calculated the location of the body C of M in each frame of film examined. Previous investigations have discussed the path of the body C of M with reference to a fixed point: on the pelvis (54,55,85), the top of the head (71) and a neck target (68,69,70). Although these investigations did not attempt to account for the changing position of the body C of M, they did report peak-to-peak vertical displacements similar to those observed in the present investigation.

Inman et al. (53) stated that there was no difference between the paths of the top of the head and a fixed point on the sacrum. In view of the complexity of determining the location of the body C of M over a large number of frames and the fact that in the present investigation its path did not diverge appreciably from that of the top of the head, it might be suggested that the path of a fixed point is a satisfactory substitute. As well, such a fixed point can be followed by the naked eye, as would be the case in the clinical or practical situation.

2. Lateral - Medial Displacement of The Hip

The side-to-side displacement of the body during normal forward walking has also been discussed with reference to a fixed point: in the central area of the pelvis (30,54,86), and the head (68,69,70,71). These curves have generally been described as low amplitude and sinusoidal, reaching their peaks at mid-stance of alternate legs (68,69,70, 71,86).

The present investigation utilized the instant of initial foot-floor contact as the zero reference point from which lateral-medial

displacements of the lateralmost point on the left hip were measured. The displacements of the lateralmost point on the left hip, in the frontal plane, were similar during backward and forward walking cycles (Tables VI and X, and Figure 14). Within each gait the mean lateral displacement was significantly greater than the mean medial displacement. Comparing displacements during both gaits, the mean backward lateral displacements did not differ significantly, while the mean medial displacement during backward walking was significantly greater than the mean medial displacement observed during forward walking. The mean peak-to-peak lateral-medial displacement during backward walking did not differ significantly from the mean displacement during forward walking (Appendix C).

During both gaits the occurrence of the peak lateral and medial displacements did not correspond with a particular specific event, eg. malleoli-even. The peak displacements during backward walking occurred prior to malleoli-even, while during forward walking peak displacements occurred after malleoli-even.

The peak-to-peak lateral-medial displacements observed in the present investigation were slightly greater than the displacements reported by previous investigators for the body C of G (30,54,86) and for the hip (31), but were not as great as those displacements reported for the top of the head (68,69,70,71).

The present investigation examined the path of the lateralmost point on the left hip during backward and forward walking cycles. Only one previous investigation was located which examined the frontal displacement of the hip during forward walking. In this case the path of a fixed point in the center of the pelvis was described in reference to the frontal displacement of the hip (30). However, in a later publication

utilizing the same data, the hip displacement was described with respect to the anterior superior iliac spine (31). In both cases the displacement was given as approximately 5.08 cm (30,31), but not discussed in depth.

The present investigation is in general agreement with these displacement curves presented for the hip (30,31). However, the present investigation observed a displacement curve which followed a course on both sides of the line of progression, mean 3.44 $\pm$ 0.63 cm laterally and mean 1.72 $\pm$ 0.31 cm medially. Eberhart et al. (30,31) reported a displacement curve which remained primarily on one side of the line of progression, approximately 5 cm laterally, and which crossed over to the other side medially for a short distance and a short time just before the termination of the walking cycle. Both studies utilized the initial foot-floor contact position as the zero reference point on which measurements were based.

Differences between the curves presented in these publications and that observed in the present investigation may lie largely with the exact point at which the measurement was taken and/or individual subjects. Only one subject was examined in each case, over one trial (30,31), as compared to nine trials in the present investigation.

3. Horizontal Velocity

Eberhart et al. (30) discussed the forward velocity of the body C of G represented by the greater trochanter of the femur and also utilized force plate data to calculate the forward velocity of the body C of G. Murray et al. examined forward velocity measured at the head (71) and a neck target (68,69,70). Both groups of investigators reported forward velocity peaks at the three floor-contact instances during the walking cycle. That is, at points where the body C of G was near its vertical low. Forward velocity lows were observed near the two C of G

high points, near mid-stance of alternate legs.

In the present investigation the mean horizontal velocity during forward walking was greater than the mean horizontal velocity observed during backward walking, at each of three measurement points (Table IV). When considered over 5% intervals of the respective walking cycle, erratic changes in the forward and backward horizontal velocities measured at the calculated body Center of Mass, were observed in the present investigation (Table XII of Appendix A). Forward and backward horizontal velocities did not lurch in a rhythmical manner and no consistent pattern was readily discernible during either gait. However, the mean backward and forward horizontal velocities during vertical ascent of the body were slightly lower than the mean horizontal velocities during trunk descent (Table VII). Overall, the forward and backward horizontal velocities did decrease slightly as the body descended. However, within each gait the mean ascending horizontal velocity did not differ significantly from the mean descending horizontal velocity (Appendix C).

V. JOINT EXCURSIONS

The joint excursions, or sagital rotations, of the left lower extremity observed in the present investigation are similar to graphical illustrations presented by other investigations (30,68,69,70,71) A brief synopsis of joint motion follows. Maximum ranges of motion have been indicated because these ranges approximate the minimum ranges of motion necessary for the subject to walk normally. Figure 15 and Tables XIII and XIV illustrate joint excursions.

1. Hip

Forward: At heel-strike the hip was moderately flexed (mean 19°). It gradually extended throughout most of stance phase, reaching walking

cycle maximum extension (mean 16°) near heel-strike of the contralateral foot. Rapid flexion took place throughout most of the swing phase, reaching walking cycle maximum (mean 26°) about three-quarters the way through swing phase. A brief period of extension occurred just before heel-strike to re-attain a mean 19° flexion by heel-strike.

Backward: Beginning from a walking cycle maximum extension (mean 10°) at toe-strike, the hip gradually flexed throughout most of the walking cycle to reach maximum flexion (mean 25°) just before malleoli-even of swing phase. It then rapidly extended throughout late swing sub-phase to re-attain a position of extension (mean 9°) in preparation for the next toe-strike.

Whether or not the hip joint is capable of extension beyond 0° is a matter of question (48,83). Extension beyond 0° may be the result of pelvic tilting and/or rotation and/or lumbar extension. These factors were not controlled for in the present investigation.

2. Knee

Forward: At heel-strike the knee was near complete extension (mean -3°). It flexed throughout heel-strike sub-phase to attain its stance phase maximum (mean 18° of flexion) near the end of this sub-phase. Gradual extension followed during mid-stance sub-phase, reaching -6° extension near the end of this sub-phase. Thereafter, the knee flexed rapidly, beginning near toe-off, and continued to walking cycle and swing phase maximum flexion (mean 71°) near the mid-portion of early swing sub-phase. It then underwent rapid extension during late swing sub-phase regaining maximum extension

(mean -3°) just before heel strike.

Backward: From a position of flexion (mean 52° at toe-strike) the knee extended gradually throughout stance phase, reaching walking cycle maximum extension (mean -2°) just prior to heel-off and the beginning of swing phase. It then underwent rapid flexion in order to permit the swinging leg to move backward under the body. Maximum flexion (mean 67°) was not achieved until the middle of late swing sub-phase. Thereafter the knee extended until the next toe-strike, re-attaining a mean 51° flexion by this time.

3. Ankle

Forward: A brief period of plantarflexion followed heel-strike in order to permit a smooth descent of the forefoot to the floor. Having achieved foot-flat, and maximum stance phase plantarflexion (mean 3°), the ankle dorsiflexed gradually, reaching walking cycle and stance phase maximum (mean 12°) near the end of mid-stance sub-phase. During push-off sub-phase the ankle again plantarflexed, reaching walking cycle and swing phase maximum (16°) just after toe-off and the beginning of the swing phase. Gradual dorsiflexion then followed, reaching swing phase maximum (mean 6°) just before heel-strike.

Backward: Toe-strike was made in near neutral position (mean 2° dorsiflexion) and was followed by rapid dorsiflexion, reaching stance phase and walking cycle maximum (mean 22°) near the end of toe-strike sub-phase, until the end of this sub-phase. Plantarflexion followed, reaching stance phase and walking cycle maximum (mean 6°) near toe-off, and then changed to a dorsiflexion pattern, reaching swing phase maximum (mean 9°) just before malleoli-even.

Plantarflexion to a swing phase maximum (mean 0^{o}) followed as the foot approached toe-strike, but changed to a brief period of dorsiflexion, reaching a mean 3^{o} at toe-strike.

Wright et al. (107) reported that ankle joint excursion during stance and swing phases of backward walking were reversals of the joint excursion patterns observed during the corresponding phases of forward walking. As well, an increased overall range of motion was reported at the ankle during backward walking. In the present investigation the backward walking pattern was found to be a general reversal of the forward walking pattern at all three joints, hip, knee and ankle, when stance phases were compared and when swing phases were compared. The patterns were not exact reversals, but close approximations.

During forward walking the hip and the knee demonstrated slightly greater total ranges of motion. At the ankle a similar total range of motion was observed during backward walking. However, this range of motion was achieved through greater dorsiflexion and less plantarflexion than was observed during forward walking.

VI. ELECTROMYOGRAPHY

1. Electrical Activity

The electromyographic sequence of activity was detected by means of surface electrodes placed over the belly of selected muscles. An electrical integrator was not utilized and it was recognized that the electrical activity detected (raw EMG) represented a summation of the detectable electrical activity in the area of the particular electrodes.

Electromagnetic interference was minimal at the time of final filming owing to the lowered level of electrical useage in the general testing area early on Sunday mornings. The subject had worn the apparatus on several occasions and stated that he felt no discomfort or hindrance to his normal walking patterns resulted.

The overall sequence of electrical activity observed during forward walking was similar to that reported by other investigators (8,30,91,92). Differences between previous investigations and the present investigation might be largely attributed to the fact that the EMG criteria utilized in the present study were relatively conservative. The muscle action potentials were at least 25% that observed at maximum intensity during that walking cycle before the muscle under consideration was judged to be electrically alive. As well, all three trials for each muscle had to be judged active before the muscle was considered to be consistently active. Other investigators have utilized a variety of criteria to evaluate the electromyogram. Graded scales, numerical and percent maximum, have been utilized (13,14,15,29,30,63,85), while other investigators have reported EMG in terms of active and non-active (7,8,11,12,42,66). Of this latter group only Battye and Joseph (8) specified a critical EMG value. Muscles were considered to be electrically active if the EMG amplitude was consistently 15% greater than peak electrical interference value.

Although muscular activity is responsible for movement of the limbs in a non gravity situation, it should be recognized that without the resistance, friction, offered by the ground, locomotion as we know it would be impossible (30,31,33,54,55). As well, without

the use of gravity walking would require much more energy (30,75). For these reasons muscles do not act as groups of prime movers and antagonists in the traditional anatomical sense during walking (30). Their roles during locomotion, where the foot is fixed, and free movement of the limb are out of phase (3).

Sutherland (92) emphasized that the realistic appraisal of a movement requires evaluation of all the other muscles which can affect the movement. Since it is not possible to precisely state the action of one muscle during walking, it is even more difficult to state how groups of muscles interact.

Previous authors have emphasized the theoretical nature of electromyographical analysis in gait studies (30,75). It is not possible to state with absolute certainty the precise function of a muscle, owing to the free limb positions and the large number of muscles simultaneously active. However, electromyography is the most effective means available of detecting muscular activity, and muscular activity is the basis of human movement (3). Although absolute precision is not possible, an improved understanding of normal walking can still be achieved.

2. EMG Modification

Inman et al. (53) and Ralston et al. (82) have pointed out that electrical activity per se (EMG) is not a precise index of contraction and/or tension of the muscle concerned. Recent work involving the human rectus femoris muscle demonstrated time lags of 30-40 msec between the onset of electrical activity and the onset of joint motion. Time lags of 200-350 msec occurred between cessation of electrical activity and the cessation of musclular tension and/ joint motion. For these reasons the authors suggested

that much of the electromyographical work carried out to date, particularly in relation to gait studies, might be re-evaluated in view of these time lags. In support of this suggestion it is emphasized that proper appreciation of muscle involvement in movement is more related to the duration of contractile activity than merely to the duration of electrical activity. EMG work, to date, has generally been descriptive of electrical activity and has not incorporated time lag information into its analysis.

Presently it is unclear as to precisely how long these time lags are, and if there is a different time lag for each muscle or muscle group. Incorporation of time lag data into EMG research might best await further investigation so that consistent and uniform interpretation of electromyographical data is forthcoming. However, it is apparent that major alterations in the interpretation of EMG data may be necessary if these time lags are demonstrated to be consistent and universal.

VII. INTEGRATED ANALYSIS OF THE BACKWARD WALKING CYCLE

Detailed analysis of the forward walking cycle has been provided by previous authors (30,31,33,77) and will not be repeated here. Of primary interest in the present investigation was the backward walking cycle, which will be considered in terms of its phases, sub-phases and specific events, combining kinematic and kinetic description. Figures 18 and 19 summarize temporal, spatial and electromyographical information during backward walking.

A. Stance Phase

1. Toe-Strike Sub-Phase (Toe-Strike to Heel-Down: 0.0% - 15.5%)

The functional demand during the toe-strike sub-phase was

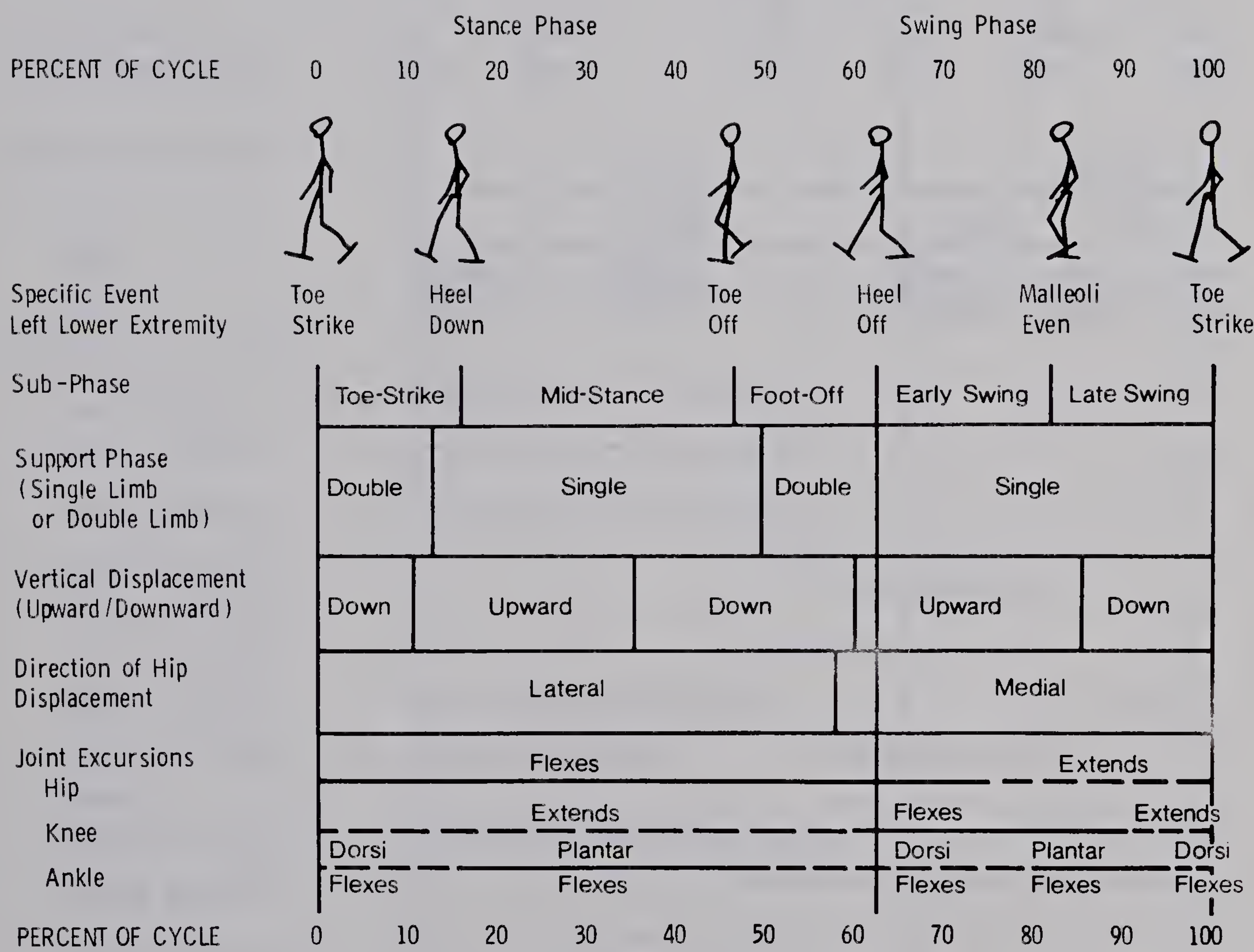


Figure 18: Summary of temperol and spatial parameters of the backward walking cycle.

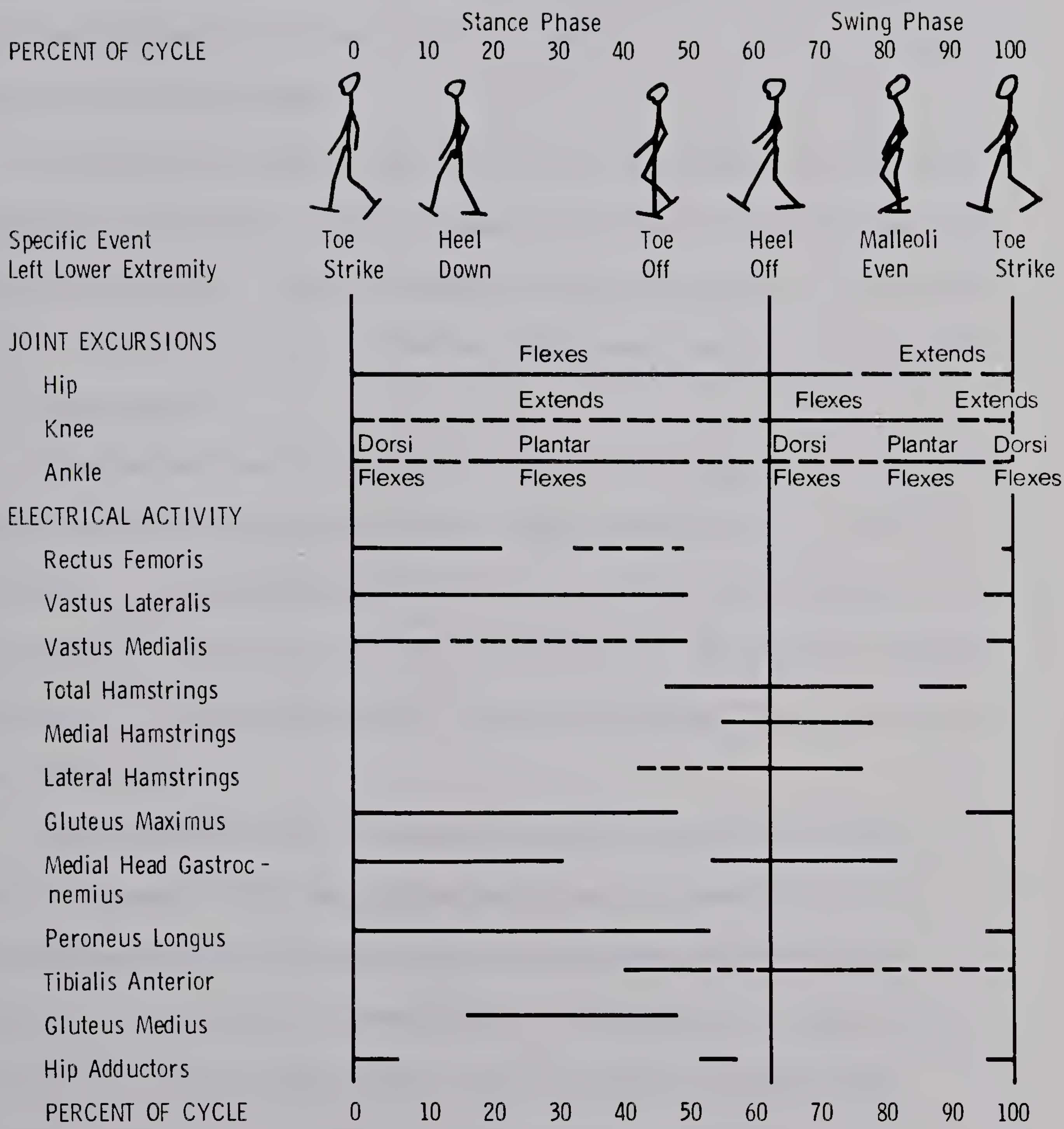


Figure 19: Summary of electromyographical sequence of activity during backward walking.

smooth weight transference to and acceptance by the new stance leg, without impeding backward travel. Toe-strike sub-phase was primarily a period of double limb support, but also involved a short period of single limb support as the contralateral swing phase commenced just prior to the end of this sub-phase.

During this initial foot-floor contact sub-phase the body C of M descended to its lowest point, a mean 2.63 cm below its level at the instant of toe-strike. This low point occurred just prior to the termination of the first period of double limb support and the beginning of single limb support.

Preparation for the following single limb support phase necessitated a lateral shift of the pelvis toward the stance, or weight bearing side. This lateral shift was well under way and was near its lateral limit by the end of toe-strike sub-phase. Through the lateral shift body C of M was moved toward the weight bearing foot to assist in single limb balance.

Ankle dorsiflexion throughout toe-strike sub-phase served primarily to permit shock absorption and a smooth transference of body weight onto the new stance foot, and a gradual termination to the body C of M's descent. Dorsiflexion terminated at the end of the first period of double limb support and the onset of single limb support. Gradual knee extension and hip flexion throughout this sub-phase served to minimize the extent to which the body C of M descended. The combined joint activity permitted minimal impediment of backward travel and minimized the loss of backward momentum. By the time that the foot-flat position had been achieved the ankle had undergone a backward walking cycle maximum dorsiflexion (mean 22°),

as compared to a forward walking cycle maximum dorsiflexion (mean 12°), observed near heel-off of forward walking.

The gastrocnemius and the peroneus longus were electrically active throughout this sub-phase to control ankle dorsiflexion eccentrically and functioned chiefly in shock absorption and the smooth transference of body weight onto the new stance foot. The peroneus longus also acted to limit the tendency toward ankle inversion at this time.

The quadriceps muscles were active in control of knee extension and resisted forward buckling of the knee while the body C of M was behind the knee joint. The rectus femoris and the hip adductors acted to flex the hip and pull the body over the stance foot, now that toe-strike had been made and resistance was offered by the floor. Along with momentum, the hip flexor activity was chiefly responsible for pulling the body over the stance foot and assisting with backward propulsion.

The contraction of the gluteus maximus throughout toe-strike sub-phase served to resist the tendency of the pelvis to rotate forward with the hip flexor contraction, and in the maintenance of upright trunk stability and posture.

2. Mid-Stance Sub-Phase (Heel-Down to Toe-Off: 15.5%-45.7%)

Body weight had been transferred to and accepted by the stance foot during late toe-strike sub-phase. The body now moved through an entire sub-phase of single limb support and balance, all-the-while maintaining backward progression.

The body C of M entered mid-stance sub-phase just after reaching its vertical low near the end of the first period of double limb

support. It then rose rapidly to reach a vertical high just after malleoli-even, the approximate mid-point of the single limb support period. The lateral displacement of the hip reached its peak just prior to malleoli-even of mid-stance sub-phase. By the termination of mid-stance sub-phase both the vertical and the lateral displacement curves were returning toward their toe-strike levels.

The knee and ankle continued to gradually extend during mid-stance sub-phase, while the hip flexed gradually. As the body continued to progress backwards the stance foot moved from a position behind the body to one in front of the body. Subsequently, the body C of M rose until the stance foot was under the body and then began to descend once again as the foot moved in front of the body. Throughout mid-stance sub-phase the stance leg continued to lengthen, however, the perpendicular distance from the hip to the ground increased first, until just after malleoli-even, and then decreased. Knee extension did not reach maximum level at malleoli-even of mid-stance sub-phase, because this would have resulted in an abnormal vertical rise of the body C of M and increased energy cost. By combining stance leg extension and swing leg flexion the vertical rise of the body C of M was kept to a minimum and energy cost minimized.

The vastus lateralis maintained activity throughout, while the vastus medialis demonstrated inconsistent electrical activity throughout, mid-stance sub-phase. The rectus femoris was active during the latter portion of the mid-stance sub-phase. These muscles all act to extend the knee, the rectus femoris also serving as a hip flexor. Hip flexion and knee extension until malleoli-even of mid-

stance sub-phase served primarily to pull the body backwards over the stance foot. After this point the thigh was relatively vertical and continued hip flexion was largely passive. The continued knee extension served to provide backward propulsion.

The gluteus medius commenced electrical activity soon after the swing phase of the contralateral extremity had begun (heel-off had been made). This contraction served to prevent abnormal drop of the contralateral hip, making it more difficult to bring the backward swinging leg under the body by decreasing the perpendicular distance to the floor and necessitating increased swinging leg knee flexion and/or increased elevation of the body C of M via the stance leg. In both instances energy cost would have risen abnormally. The gluteus medius was also active in pelvic stabilization, while the continued gluteus maximus activity was primarily concerned with trunk stabilization.

The gastrocnemius was active during the first half of mid-stance sub-phase, while the peroneus longus was active throughout. Both muscles functioned to maintain the foot-flat position, as the body weight continued to move from in front to behind the stance foot. As the body weight moved further behind the stance foot, the ankle plantarflexion became largely passive. Peroneus longus activity at this time insured that the foot remained on the floor.

3. Foot-Off Sub-Phase (Toe-Off to Heel-Off: 45.7% - 62.1%)

The contralateral foot was still swinging backward during early foot-off sub-phase and made floor contact approximately one-quarter of the way into this sub-phase. Thus, foot-off sub-phase was partially a period of single limb support and balance, but largely one of double limb support and weight transference to the contra-

lateral extremity.

The descending body C of M reached its left toe-strike level, zero point, almost at the same instant as right toe-strike was made. These instants in time corresponded with the initiation of the first and second double limb support periods. The body C of M continued descending throughout most of foot-off sub-phase, reaching its second vertical low, a mean 2.09 cm below the toe-strike level, near the end of the second period of double limb support. Both vertical lows during backward walking were reached near the ends of double limb support periods and were of similar magnitude.

By the beginning of the foot-off sub-phase the left hip had commenced to move, from a position near its peak lateral displacement, rapidly medialward. This pattern of movement was indicative of the transference of body weight from single limb support to double limb support. Near the same time as the vertical low was reached, the lateral displacement curve for the hip again reached its zero point, or toe-strike displacement.

The knee and the ankle changed patterns of movement at opposite ends of foot-off sub-phase. The knee changed from extension to flexion, while the ankle changed from plantarflexion to dorsiflexion at the beginning of the sub-phase. Knee flexion occurred in preparation for swinging the leg under the body, to shorten the limb. Ankle dorsiflexion served to achieve toe-off and the termination of the foot-flat position, thus avoiding plantarflexion which was no longer of practical value since the body C of M was already well behind the stance foot and balance was now primarily achieved with the contralateral foot.

The continued knee extension and hip flexion during the foot-off sub-phase was largely passive with the foot in front of the body C of M. Joint excursions and backward travel combined to lower and transfer the body C of M onto the new stance foot.

The quadriceps continued to assist with knee extension and backward propulsion during only the first portion of foot-off sub-phase. Thereafter the body was sufficiently behind the left foot and the knee moved passively into further extension, guided by the hamstring muscles, contracting eccentrically. The gluteus medius and the gluteus maximus maintained electrical activity until almost precisely toe-strike of the contralateral foot, the initiation of the second period of double limb support. The gluteus medius was no longer required to control drop of the contralateral hip now that ground contact had been made. Assuming a reciprocal pattern of activity on the contralateral side, the right gluteus maximus was already active to stabilize the trunk on the pelvis.

Tibialis anterior activity was associated with active dorsi-flexion of the ankle observed throughout foot-off sub-phase. Gastrocnemius activity during the later portion of foot-off sub-phase served to assist at both the knee and the ankle providing stability through co-contraction.

The brief burst of hip adductor activity observed just prior to the end of foot-off sub-phase served as an eccentric control of backward pelvic horizontal rotation on the swing side. The peroneus longus activity observed during the first portion of the sub-phase served to counteract the inversion tendency of the ankle dorsiflexors.

B. Swing Phase

1. Early Swing Sub-Phase (Heel-Off to Malleoli-Even: 62.1% - 81.4%)

During early swing sub-phase the foot broke contact with the ground, travelled backward and caught-up to the stance leg at malleoli-even. The contralateral extremity began the single limb support and balance portion of its stance phase at the start of this sub-phase.

Early swing sub-phase was a phase of C of M transition from its second vertical low, near the beginning, to a second vertical high, near the end. The vertical high point occurred just after the termination of early swing sub-phase. During this period of contralateral stance phase the vertical displacements of the trunk were attributable to motion of the contralateral extremity.

Shortly before malleoli-even of swing phase, the left hip reached its greatest medial deviation. This displacement was not as great in magnitude as the lateral displacement observed during the stance phase. By this time the body weight was borne solely on the contralateral extremity and the medial deviation served to place the body C of M over the contralateral stance foot to facilitate single limb balance and support.

Early swing sub-phase combined ankle dorsiflexion and knee flexion to shorten the swinging extremity and further facilitate backward passage under the body. Owing to the extent of knee flexion at this time the instant of malleoli-even was attained while the hip was still in approximately 20 degrees of flexion. The rate of knee flexion beginning at the onset of early swing sub-phase was rapid, moving from 4 to 55 degrees before malleoli-even. Hip extension did

not begin until approximately two-thirds of the way through this sub-phase. Knee flexion, rather than hip extension, was primarily responsible for heel-off and backward movement of the swing heel.

The hamstrings were the major muscles concerned with hip extension during backward walking, particularily initiating backward movement of the leg. The hamstrings ceased electrical activity near the end of early swing sub-phase and momentum was largely responsible for carrying the swinging leg backward to its toe-strike position.

The hamstrings were the main knee flexors during early swing sub-phase, but may have been assisted by the gastrocnemius. The tibialis anterior was active during early swing sub-phase to provide dorsiflexion so that knee flexion need not be excessive during the backward swing in order to clear the toes.

2. Late Swing Sub-Phase (Malleoli-Even to Toe-Strike: 81.4%-100.0%)

During late swing sub-phase the left lower extremity reached behind the body to make floor contact once again. The contralateral foot, in stance phase, made toe-off near the middle of late swing sub-phase. Although late swing sub-phase was totally a period of single limb support, the stance foot was in only partial floor contact much of the time.

During late swing sub-phase the body C of M descended from its swing phase high to near its zero point (mean 0.02 cm) at the instant of toe-strike. This instant marked the end of that stride and also corresponded with the onset of another double limb support period. Vertical motion was under control of the contralateral extremity moving through its stance phase.

Throughout swing phase the left hip was displaced toward the

supporting the right foot. Late swing sub-phase was a period of continued movement of the pelvis back to its zero position at the end of the walking cycle.

Late swing sub-phase was characterized by ankle plantarflexion designed to lengthen the backward reaching extremity prior to floor-contact. Although plantarflexion reduced toe-clearance, the continued knee flexion provided adequate clearance for the toes. Ankle dorsiflexion just prior to toe-strike was aimed at cushioning toe contact and insuring that ground contact was made with the plantar surface of the toes, rather than the dorsal surface.

Knee flexion reached its peak near the mid-portion of late swing sub-phase and then changed to knee extension. The return of hip extension to zero and peak knee flexion occurred simultaneously. Because the thigh was now in a relatively vertical position and the ankle was plantarflexing, maximum knee flexion was required to clear the backward traveling toes. Continued hip and knee extension during late swing sub-phase combined to lengthen the backward reaching extremity so that ground contact could be made without an abrupt change in the path of the body C of M.

Late swing sub-phase was a period during which momentum, generated by earlier muscular activity, carried the limb backwards to the next toe-strike. The brief period of hamstring activity observed during late swing sub-phase was necessary to maintain momentum of the backward swinging leg and/or to insure adequate knee flexion to clear the toes. Inconsistent electrical activity of the tibialis anterior was observed throughout this sub-phase and may have been related to

low level contraction of the tibialis anterior.

Just prior to toe-strike electrical activity was observed in the quadriceps, gluteus maximus, peroneus longus and the hip adductors. The rectus femoris and the hip adductor activity just prior to toe-strike served to decelerate the thigh and to limit the extent of backward hip extension and subsequently, stride length. Peroneus longus activity at this time resisted the tendency toward ankle inversion associated with plantarflexion. The gluteus maximus was active to limit the tendency toward forward rotation of the pelvis as the rectus femoris contracted and functioned to stabilize the trunk on the pelvis. The quadriceps muscles served to limit the tendency toward forward knee buckling at the instant of toe-strike and following toe-strike.

CHAPTER SIX

SUMMARY AND CONCLUSIONS

I. INTRODUCTION

Walking backwards is a form of bipedal plantigrade progression. Although utilized to a lesser extent than is forward walking, it is never-the-less a daily component in the translation of the body center of mass (C of M) from one place to another. The significance of backward movement becomes more readily apparent in situations of physical handicap and during sporting activities. Similarily to walking forwards, the ability to walk safely backwards is taken for granted by those who can perform this activity safely and without difficulty.

The present investigation examined one aspect of backward movement, walking backwards at a free or comfortable speed, employing a specific walking technique. By providing information describing what is considered, by the author, to be the basic pattern of backward movement a beginning has been made toward the improved understanding and greater appreciation of backward locomotion as a whole.

The present investigation examined the backward walking gait of only one subject. It was recognized that the external validity was subsequently low and the degree of confidence in generalization from a non random sample of one to a population as a whole must also be low.

A substantial volume of information was gathered in the present study, describing both the backward and the forward walking cycles, examined over nine walking cycles each. Included in this information

was the displacement of the body C of M, which was calculated for each frame of film examined, and the electromyographic sequence of activity of twelve lower extremity muscles. Previous investigations have generally examined fewer parameters and have been confined to the forward walking cycle alone.

The present investigation utilized a simple two camera synchronization technique and incorporated EMG and subject activity into one frame of film, thereby eliminating the need for a separate EMG record. The equipment and the filming technique are readily adaptable to a variety of studies, which can be carried out indoors or outdoors.

Of particular significance in the present investigation was the utiliziation of electromyographical and cinematographical techniques designed to minimize the physiological and psychological influence the experimental situation. The EMG system provided good quality recordings yet minimized the physical impediment to the subject. The cinematographical recording system provided a permanent and detailed record, and permitted synchronization of the EMG and subject activity without the need to attach additional equipment to the subject.

Inman (54), commenting on personal experience in a large number of gait investigations, stressed that there is no such thing as the average man. Individual variations tended to disappear when averaged over a large number of subjects and upon re-examination of individual

subject performances it was noted that the averaged values themselves did not apply to a single one of the subjects. Averaged values simply represent the basic pattern of movement upon which individual variations are superimposed. However, it is necessary to understand the basic pattern in order to understand the variations seen in normal, and, particularly pathological gaits (54,55).

Human bipedal locomotion has been termed a phenomenon of extraordinary complexity (86). Many different investigative techniques must be utilized in order to obtain quantitative data on specific aspects of the entire motor act of walking and no one technique can yield all the desired information (30,86).

Presently only the most obvious, or apparent, factors can be integrated and even these cannot, with absolute certainty, be related to their order of importance (30). It is not possible to completely describe locomotion in anything like its actual complexity because there are gaps in the knowledge of how events take place and how they are coordinated. Eberhart et al (30), in 1947, suggested that the synthesis of all the elements which simultaneously participate to achieve locomotion appears too difficult for early attainment. A great deal more information is presently available describing the normal forward walking cycle, however, a complete understanding of the normal walking cycle has not been achieved.

II. SUMMARY

The purpose of this study was to provide basic information descriptive of the backward walking cycle. Temporal, spatial and electromyographical data were gathered by means of two synchronized

16 mm films and a four channel electromyographic system.

One volunteer male subject, who was judged to be in excellent physical condition and who had sustained no significant lower extremity injuries, was examined. The subject was familiarized with the equipment and the task over a period of four weeks.

Camera One photographed the subject's lateral aspect, while Camera Two photographed the subject's anterior aspect, as well as the oscilloscope screen. A total of twelve muscles, four at a time, were examined via surface electromyography. An impulse generator was used to simultaneously activate the internal timing lights within each camera. Frame-for-frame synchronization of the two films was achieved by matching the interval timing light traces along the edges of both films. The subject completed three backward and three forward trials with each electrode sequence, or positioning. All walking was carried out at a free speed selected by the subject to be 'normal' and 'comfortable' for him.

The backward walking cycle was first divided into component events, phases and sub-phases which corresponded to the divisions of the forward walking cycle. Temporal, spatial and electromyographical data was gathered from the two synchronized film records and presented by means of tables and graphs, illustrating both seconds duration and the percent of the respective walking cycle.

The 'principle of moments' was utilized to calculate the location of the body C of M in selected frames of Film One and the cosine law was utilized to calculate the joint angles of the left lower extremity in these same frames of film. The lateralmost point on the left hip was determined for corresponding frames of Film Two.

Electrical activity was classified as active or not active, and was expressed as percent activity duration of the respective walking cycle.

III. CONCLUSIONS

Within the delimitations of the design of the study and the limitations of the acquisition of the data, the following conclusions are drawn:

1. The use of an impulse generator to synchronize two film records was a simple, inexpensive and effective means of matching two views of subject activity and the simultaneous electromyograms.

2. The use of a split lens to permit sharp focus on both the subject and the oscilloscope screen was a simple, inexpensive and effective means of recording subject activity and the simultaneous electromyograms on one film. By doing so the need for a separate EMG record, which later needed to be correlated with both lateral and anterior views of the subject, was eliminated.

3. The terms commonly utilized to describe the forward walking cycle have been modified to describe the backward walking cycle. Corresponding phases, sub-phases and specific events exist in both gaits.

4. In terms of seconds duration, the walking cycle as a whole, and both stance and swing phases were of greater duration during backward walking. In terms of percent duration of the walking cycle, forward stance phase was of significantly greater duration than backward stance phase and backward swing phase was of significantly greater duration than forward swing phase.

5. The duration of (seconds and percent of the walking cycle)

of double limb support period, both periods combined, was similar for both gaits. First and second double limb support periods were of similar duration during backward walking. However, during forward walking the first period was of significantly greater duration than the second period of double limb support.

6. During backward stance phase, mid-stance sub-phase was of significantly greater duration (seconds and percent of the walking cycle) than either toe-strike or foot-off sub-phases, which were of similar duration. During forward stance phase, the duration (seconds and percent of the walking cycle) of mid-stance sub-phase was significantly greater than the duration of push-off sub-phase, which was significantly greater than the duration of heel-strike sub-phase.

7. During backward swing phase, early and late swing sub-phases were similar in terms of seconds duration and proportion of the backward walking cycle. During forward swing phase, late swing sub-phase was of significantly greater duration than early swing sub-phase.

8. Mid-stance sub-phase was the longest sub-phase (seconds and percent of the walking cycle) observed during both gaits. Backward mid-stance sub-phase was of significantly greater duration than forward mid-stance sub-phase. Backward initial floor-contact sub-phase (Toe-Strike) was of significantly greater duration than was forward initial floor-contact sub-phase (Heel-Strike). Forward pre-swing sub-phase (Push-Off) was of significantly greater duration than was backward pre-swing sub-phase (Foot-Off). Backward early swing sub-phase was of significantly greater duration than was forward early swing sub-phase. Backward and forward late swing sub-phases were of similar seconds duration. However, forward late swing sub-phase represented a

significantly greater proportion of the forward walking cycle than backward late swing sub-phase represented of the backward walking cycle.

9. Backward walking cadences and horizontal velocities were slower than forward walking cadences and horizontal velocities.

10. Backward walking stride and step lengths were shorter than forward walking stride and step lengths. During each gait, right and left step lengths represented similar distances and proportions of the stride length.

11. Within each walking cycle the body C of M was displaced through two vertical high points and two vertical low points. During backward walking the low points occurred near the end of double limb support periods. During forward walking the low points occurred near the start of double limb support periods. During both gaits the high points occurred shortly after malleoli-even, during mid-stance of alternate legs.

12. The peak-to-peak vertical displacements during backward walking were significantly greater than the peak-to-peak vertical displacements observed during forward walking. Backward walking was characterized by higher high points and lower low points in terms of displacement of the body C of M relative to its position at the instant of floor-contact.

13. The vertical displacements of the top of the head and the vertical displacements of the calculated body C of M were similar. Only two, of thirty-eight individual comparisons were found to be significantly different at the .05 level of significance.

14. Peak-to-peak displacements of the lateralmost point on the left hip during backward walking were similar to displacements during

forward walking, when measured using the initial foot-floor contact as the zero reference point.

15. Within each gait lateral hip displacements were significantly greater than medial hip displacements. Lateral displacements during both gaits were similar, while the mean medial displacement during backward walking was significantly greater than the mean medial displacement during forward walking.

16. Changes in the horizontal velocity of the body C of M (calculated over 5% intervals of the respective walking cycle) during both backward and forward walking, were small and erratic. A consistent pattern was noted only after the mean ascending horizontal velocity was compared with the mean descending horizontal velocity. In this case the mean horizontal velocity during both gaits, decreased slightly as the body C of M ascended to its vertical highs and velocity increased slightly as the body C of M descended to its vertical lows. However, within each gait the mean ascending horizontal velocity did not differ significantly from the mean descending horizontal velocity.

17. The total range of motion observed at the hip and the knee was slightly greater during forward walking. The ankle demonstrated a similar total range of motion during backward walking, however, this range was achieved through increased dorsiflexion and decreased plantarflexion as compared to forward walking ankle excursions.

18. During backward walking the muscles tended to be consistently electrically active for longer periods of time than during forward walking. However, a greater degree of inconsistent electrical activity was observed during backward walking, as compared to forward walking.

IV. RECOMMENDATIONS

1. That further investigation of backward walking be undertaken, utilizing a larger number of subjects.

2. That additional information describing the backward walking cycle be gathered. A third synchronized camera placed orthogonal to the other two, eg. top viewing, could provide information on the axial rotation of body segments. Force plates incorporated into the walkway could provide information on floor reactions. Such procedures can be carried out without hindering the subject to a further extent.

3. That investigation of other movement techniques be undertaken: moving sideways, running forwards and backwards, pivoting, jumping, skating and cycling. These activities can all be examined in relatively normal environments with minimal hindrance to the subject using the techniques outlined in the present investigation.

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APPENDIX A: DATA SUMMARY TABLES

TABLE VIII

Mean Instants of Occurrence of Specific Events During Backward and Forward Walking Cycles (means of nine walking cycles)

Event: Left Lower Extremity	Event: Right Lower Extremity	Percent of Walking Cycle (%) Mean	Percent of Walking Cycle (%) Standard Deviation	Time (sec) Mean	Time (sec) Standard Deviation
BACKWARD					
TS		0.0	0.0	0.0000	0.0000
	HO	12.0	0.6	0.1529	0.0103
HD		15.5	1.9	0.1968	0.0245
	ME	31.1	1.0	0.3956	0.0172
TO		45.7	2.0	0.5791	0.0192
	TS	49.5	1.0	0.6268	0.0194
HO		62.1	0.7	0.7874	0.0207
	HD	72.6	3.1	0.9192	0.0376
ME		81.4	1.2	1.0320	0.0298
	TO	90.2	3.1	1.1428	0.0464
TS		100.00	0.0	1.2671	0.0322
FORWARD					
HS		0.0	0.0	0.0000	0.0000
TD		11.9	1.4	0.1376	0.0172
	TO	13.5	0.8	0.1567	0.0103
	ME	28.5	0.8	0.3306	0.0115
HO		39.4	3.3	0.4568	0.0366
	HS	51.0	0.8	0.5924	0.0125
TO		63.2	0.8	0.7339	0.0149
	TD	66.7	1.9	0.7740	0.0272
ME		78.9	0.7	0.9155	0.0152
	HO	83.3	2.8	0.9629	0.0344
HS		100.0	0.0	1.1600	0.0125

TABLE IX

Vertical Displacements At Specific Percentages of The Backward and Forward Walking Cycles (means of nine walking cycles)

Percent of Walking Cycle (%)	BACKWARD C of M Mean	BACKWARD C of M Standard Deviation	BACKWARD Head Mean	BACKWARD Head Standard Deviation	FORWARD C of M Mean	FORWARD C of M Standard Deviation	FORWARD Head Mean	FORWARD Head Standard Deviation
	(cm)							
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	-1.90	0.77	-1.64	0.65	0.34	0.39	0.40	0.42
10	-2.45	0.84	-2.26	1.21	1.06	0.43	0.95	0.59
15	-2.09	0.96	-1.70	1.68	2.22	0.51	1.87	0.55
20	0.25	1.35	0.08	1.67	3.01	0.31	3.38	0.56
25	1.55	0.69	1.98	1.40	4.14	0.62	4.36	0.66
30	2.89	0.65	3.16	1.09	4.89	0.78	4.76	0.65
35	3.27	0.33	3.53	0.65	3.84	0.45	3.90	0.69
40	2.59	0.62	2.69	0.80	2.49	0.48	2.28	0.54
45	1.89	0.73	1.99	1.02	1.20	0.76	0.68	0.70
50	0.24	0.81	0.23	0.73	0.15	0.30	-0.12	0.31
55	-1.22	0.80	-1.44	0.85	-0.07	0.19	-0.36	0.27
60	-1.77	1.49	-2.41	1.13	0.20	0.40	0.08	0.38
65	-1.20	1.37	-1.80	1.38	1.01	0.45	0.68	0.54
70	0.10	0.91	0.04	1.15	2.34	0.39	2.44	0.73
75	1.93	0.48	1.96	0.96	3.35	0.59	3.63	0.96
80	2.58	0.79	2.75	0.61	4.42	0.38	4.38	0.46
85	2.70	0.57	2.93	0.77	3.34	0.60	3.58	0.79
90	1.69	0.65	2.05	0.69	2.00	0.55	2.11	0.66
95	0.85	0.78	1.21	0.43	0.62	0.54	0.94	0.39
100	0.02	0.24	0.17	0.21	0.00	0.29	-0.01	0.27
Peak-to Peak Displacement	6.13	0.77	6.60	0.57	5.29	0.58	5.37	0.49

TABLE X

Displacements of The Lateralmost Point on The Left Hip During Backward and Forward Walking Cycles (means of nine walking cycles)

Percent of Walking Cycle (%)	BACKWARD Mean (cm)	BACKWARD Standard Deviation (cm)	FORWARD Mean (cm)	FORWARD Standard Deviation (cm)
0	0.00	0.00	0.00	0.00
5	1.10	0.26	0.80	0.26
10	1.89	0.37	1.56	0.39
15	2.59	0.42	2.20	0.50
20	2.89	0.35	2.65	0.79
25	2.89	0.35	2.68	0.54
30	2.83	0.72	2.66	0.67
35	2.54	0.80	2.97	0.76
40	2.51	0.41	3.11	0.82
45	2.12	0.39	3.01	0.69
50	1.30	0.58	2.20	0.52
55	0.66	0.63	1.57	0.54
60	-0.48	0.59	0.86	0.56
65	-1.02	0.55	0.00	0.46
70	-1.40	0.65	-0.73	0.45
75	-2.05	0.49	-1.30	0.54
80	-1.70	0.50	-1.57	0.46
85	-1.35	0.44	-1.44	0.26
90	-1.06	0.35	-1.02	0.26
95	-0.53	0.27	-0.67	0.26
100	0.00	0.00	0.00	0.00
Peak-to-Peak Displacement	5.28	0.60	5.17	0.79

TABLE XI

Vertical and Lateral Displacements at Specific Events of The Backward and Forward Walking Cycles

Event		Vertical Displacement (cm)				Lateral Displacement (cm)	
		Head		C of M		Hip	
Left Lower Extremity	Right Lower Extremity	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
BACKWARD							
TS		0.00	0.00	0.00	0.00	0.00	0.00
	HO	-1.91	1.20	-2.24	0.77	2.22	0.29
HD		-1.32	1.67	-1.82	1.30	2.57	0.38
	ME	3.27	0.98	3.07	0.54	2.85	0.67
TO		1.37	1.10	1.57	0.78	1.99	0.46
	TS	0.24	0.65	0.42	0.56	1.40	0.59
HO		-1.73	1.22	-1.50	1.37	-0.81	0.54
	HD	0.98	1.40	0.87	1.57	-1.67	0.74
ME		2.83	0.72	2.51	0.61	-1.63	0.42
	TO	2.07	0.84	1.61	0.57	-0.91	0.42
TS		0.07	0.27	0.02	0.24	0.00	0.00
FORWARD							
HS		0.00	0.00	0.00	0.00	0.00	0.00
TD		1.38	0.68	1.31	0.57	1.83	0.48
	TO	1.78	0.51	1.73	0.45	2.16	0.49
	ME	4.65	0.62	4.80	0.76	2.68	0.56
HO		2.45	0.91	2.48	1.21	2.94	0.81
	HS	-0.19	0.30	0.07	0.30	1.98	0.62
TO		0.47	0.29	0.71	0.26	0.18	0.46
	TD	1.39	0.73	1.42	0.49	-0.42	0.50
ME		4.24	0.65	4.13	0.65	-1.53	0.42
	HO	3.53	0.86	3.36	0.40	-1.53	0.26
HS		-0.01	0.27	0.00	0.29	0.00	0.00

TABLE XII

Mean Horizontal Displacements Measured At the Body

Center of Mass During Backward and Forward Walking

Percent of Walking Cycle	BACKWARD	FORWARD
	(cm/5% division of the walking cycle)	
0	0.00	0.00
5	8.52	8.99
10	5.87	8.71
15	8.44	7.50
20	6.84	8.37
25	6.86	7.11
30	6.53	6.74
35	7.12	7.16
40	7.38	8.09
45	7.47	8.86
50	8.27	8.30
55	8.27	7.42
60	6.67	10.18
65	7.42	7.03
70	7.66	8.27
75	6.83	7.16
80	6.45	7.30
85	6.27	8.44
90	7.42	6.81
95	6.46	9.13
100	7.65	8.72

Values calculated as the difference between the means of the cummulative displacement means at the percentages of the walking cycle indicated

Displacements indicate distance travelled in the previous 5% interval

TABLE XIII

Joint Excursions of The Left Lower Extremity During Backward Walking (means of nine walking cycles)

	Hip			Knee			Ankle		
Percent of Walking Cycle (%)	Mean	Standard Deviation	Corrected Angle	Mean	Standard Deviation	Corrected Angle	Mean	Standard Deviation	Corrected Angle
0	190	2	-10	128	6	52	88	2	-2
5	189	2	-9	144	5	36	75	2	-15
10	188	3	-8	151	6	29	68	2	-22
15	185	2	-5	157	6	23	68	2	-22
20	183	1	-3	159	4	21	72	3	-18
25	181	1	-1	164	4	16	77	3	-13
30	179	1	1	166	3	14	82	3	- 8
35	177	1	3	167	2	13	87	4	- 3
40	174	1	6	168	3	12	92	3	2
45	171	2	9	170	3	10	96	2	6
50	168	3	12	173	4	7	96	4	6
55	164	2	16	175	3	5	91	3	1
60	162	2	18	178	2	2	86	2	-4
65	159	4	21	176	3	4	85	2	-5
70	156	3	24	163	4	17	84	2	-6
75	155	2	25	144	5	36	82	2	-8
80	158	3	22	127	3	53	81	2	-9
85	166	4	14	119	5	61	83	2	-7
90	171	3	9	113	4	67	86	3	-4
95	180	5	0	119	4	61	90	3	0
100	189	3	-9	129	6	51	87	2	-3

Angle expressed in degrees, + flexion and - extension of hip and dorsiflexion of ankle

Corrected Angle - converted to the nomenclature suggested by The American Academy of Orthopaedic Surgeons (48)

TABLE XIV

Joint Excursions of The Left Lower Extremity During Forward Walking (means of nine walking cycles)

Percent Walking Cycle (%)	Hip			Knee			Ankle		
	Mean	Standard Deviation	Corrected Angle	Mean	Standard Deviation	Corrected Angle	Mean	Standard Deviation	Corrected Angle
0	161	2	19	177	2	3	85	1	-5
5	165	3	15	172	4	8	93	2	3
10	166	4	14	162	1	18	92	2	2
15	170	2	10	162	2	18	88	2	-2
20	175	2	5	165	3	15	86	2	-4
25	178	2	2	168	3	12	85	3	-5
30	183	3	-3	170	3	10	82	3	-8
35	187	2	-7	173	3	7	80	2	-10
40	190	2	-10	174	3	6	78	2	-12
45	194	2	-14	171	6	9	80	3	-10
50	196	5	-16	166	3	14	81	2	-9
55	193	4	-13	154	6	26	88	4	-2
60	187	4	-7	135	4	45	104	5	14
65	179	4	1	120	3	60	106	2	16
70	168	4	12	109	3	71	97	4	7
75	161	4	19	111	4	69	91	3	1
80	160	4	20	124	3	56	89	3	-1
85	156	2	24	143	1	37	88	2	-2
90	154	5	26	164	3	16	85	4	-5
95	159	4	21	177	1	3	84	3	-6
100	161	3	19	177	2	3	84	2	-6

Angles expressed in degrees , + flexion and - extension of hip and dorsiflexion of ankle
Corrected Angle - converted to the nomenclature suggested by The American Academy of Orthopaedic Surgeons (48)

APPENDIX B: LIST OF MANUFACTURERS

EQUIPMENT MANUFACTURERS

Tektronix 564 Four Beam Oscilloscope	Tektronix Inc., Beaverton, Oregon 97077
Photo Sonics 1 PL 16 mm Cameras Photo Sonics Impulse Generator	Photo Sonics Inc. Burbank, California
Angénieux, 72 mm diameter, 12-120 zoom lenses	Angenieux Corp. Paris, France
Split Lens	Toshiba Photographic Supplies, Co. Tokyo, Japan
Strobotac Type 1531 Timing Light	General Radio Company Concord, Massachusetts
Parker 360 Electrode Paste	Parker Laboratories, Inc. Irvington, New York 07111
Hewlett Packard Two Sided Adhesive Discs	Hewlett Packard Canada Ltd. Edmonton, Alberta
Ace Athletic Wrap (polyurethane foam rubber bandage)	Protective Products Division Becton-Dickson and Co. Grande Prairie, Texas 75059
Triad V/R 100 Motion Picture Analyser	Triad Corp. Glendale, California
Bendix Digitizer Board Bendix Cursor	Bendix Corp. Advanced Products Division Farmington, Michigan
Hewlett Packard 9825A Calculator	Hewlett Packard Calculator Products Division, Loveland, Colorado

APPENDIX C SELECTED STATISTICAL COMPARISONS

I. Comparison of Mean Phase and Sub-Phase Durations During Backward and Forward Walking (see Table III for standard deviations)

SECONDS DURATION

Comparison	Walking Cycle Means Backward	Walking Cycle Means Forward	Calculated t Value
Stance Phase	0.788	0.734	6.28*
Initial Floor Contact Sub-Phase	0.197	0.138	5.86*
Mid-Stance Sub-Phase	0.382	0.319	4.04*
Pre-Swing Sub-Phase	0.208	0.277	3.85*
Swing Phase	0.480	0.426	9.06*
Early Swing Sub-Phase	0.245	0.182	8.28*
Late Swing Sub-Phase	0.235	0.245	1.60
Walking Cycle Duration	1.267	1.160	9.30*

The critical t value was ($t_{.05,16}$) 1.75

* indicates a significant difference between the two means at the .05 level

PERCENT OF THE RESPECTIVE WALKING CYCLE

Comparison	Walking Cycle Means Backward	Walking Cycle Means Forward	Calculated t Value
Stance Phase	62.1	63.3	3.57*
Initial Floor Contact Sub-Phase	15.5	11.9	4.82*
Mid-Stance Sub-Phase	30.2	27.5	2.04*
Pre-Swing Sub-Phase	16.4	23.9	5.62*
Swing Phase	37.9	36.8	3.27*
Early Swing Sub-Phase	19.3	15.7	6.70*
Late Swing Sub-Phase	18.6	21.1	5.69*

The critical t value was ($t_{.05,16}$) 1.75

II. Comparison of Mean Sub-Phase Durations During Backward Walking (see Table III for standard deviations)

SECONDS DURATION OF THE BACKWARD WALKING CYCLE

Specific Event		LS	ES	FO	MS	TS
	Mean	0.235	0.245	0.208	0.382	0.197
TS	0.197	3.77*	4.41*	0.83	12.67	-
MS	0.382	11.08*	9.87*	10.99*	-	
FO	0.208	2.29*	2.97*	-		
ES	0.245	1.11	-			
LS	0.235	-				

The critical t value was $(t_{.05,16})$ 1.75

PERCENT OF THE BACKWARD WALKING CYCLE

Specific Event		LS	ES	FO	MS	TS
	Mean	18.6	19.3	16.4	30.2	15.5
TS	15.5	4.36*	4.96*	0.98	12.79*	-
MS	30.2	11.04*	10.01*	11.48*	-	
FO	16.4	2.78*	3.44*	-		
ES	19.3	1.15	-			
LS	18.6	-				

The critical t value was $(t_{.05,16})$ 1.75

III. Comparison of Mean Sub-Phase Durations During Forward Walking (see Table III for standard deviations)

SECONDS DURATION OF THE FORWARD WALKING CYCLE

Specific Event		LS	ES	PO	MS	HS
	Mean	0.245	0.182	0.277	0.319	0.138
HS	0.138	17.09*	6.87*	8.84*	15.76*	-
MS	0.319	7.15*	13.13*	2.37*	-	
PO	0.277	2.15*	6.35*	-		
ES	0.182	15.70*	-			
LS	0.245	-				

The critical t value was $(t_{.05,16})$ 1.75

PERCENT OF THE FORWARD WALKING CYCLE

Specific Event		LS	ES	PO	MS	HS
	Mean	21.1	15.7	23.9	27.5	11.9
HS	11.9	18.59*	7.45*	9.82*	15.76*	-
MS	27.5	7.01*	12.81*	2.50*	-	
PO	23.9	2.41*	7.03*	-		
ES	15.7	16.06*	-			
LS	21.1	-				

The critical t value was $(t_{.05,16})$ 1.75

IV. Comparison of Mean Double Limb Support Periods During Backward and Forward Walking (see Table IV for standard deviations)

SECONDS DURATION OF DOUBLE LIMB SUPPORT PERIODS

Double Limb Support Period		Forward Second	Forward First	Backward Second	Backward First
	Mean	0.141	0.157	0.161	0.153
Backward First	0.153	2.31*	0.85	1.33	-
Backward Second	0.161	3.13*	0.67	-	
Forward First	0.157	3.07*	-		
Forward Second	0.141	-			

The critical t value was $(t_{.05,16})$ 1.75

PERCENT DURATION OF THE RESPECTIVE WALKING CYCLE

Double Limb Support Period		Forward Second	Forward First	Backward Second	Backward First
	Mean	12.2	13.5	12.7	12.1
Backward First	12.1	0.27	4.43*	1.51	-
Backward Second	12.7	1.06	1.86*	-	
Forward First	13.5	3.21*	-		
Forward Second	12.2	-			

The critical t value was $(t_{.05,16})$ 1.75

IV. continued

DOUBLE LIMB SUPPORT PERIOD (BOTH PERIODS COMBINED)

Comparison	Backward	Forward	Calculated t Value
Seconds Duration	0.313	0.298	1.67
Percent of Walking Cycle	24.7	25.7	1.72

The critical t value was ($t_{.05,16}$) 1.75

V. Comparison of Mean Peak-to-Peak Vertical Displacements (cm)

During Backward and Forward Walking (see Table V for standard deviations)

Direction of Displacement		Forward Head	Forward C of M	Backward Head	Backward C of M
	Mean	5.37	5.29	6.60	6.13
Backward C of M	6.13	2.51*	2.63*	1.48	-
Backward Head	6.60	4.93*	4.86*	-	
Forward C of M	5.29	0.32	-		
Forward Head	5.37	-			

The critical t value was ($t_{.05,16}$) 1.75

VI. Comparison of the Vertical Displacements (cm) of The Top of The Head and The Calculated Body Center of Mass During Backward and Forward Walking

The displacement of the top of the head was compared to the displacement of the calculated body center of mass at each of nineteen points (5% intervals) during each gait (see Table IX of Appendix A). Of a total thirty-eight comparisons during both gaits only two were found to be significant at the .05 level of significance. These comparisons are illustrated below:

Forward Walking

Percent of The Walking Cycle	Displacement		Calculate t Value
	C of M	Top of Head	
50	0.15	-0.12	1.89*
55	-0.07	-0.36	2.65*

The initial foot-floor contact position was utilized as the zero reference point on which measurements were based.
The critical t value was $(t_{.05,16})$ 1.75

VII. Comparison of Mean Lateral, Medial and Peak-to-Peak Lateral-Medial Displacements of The Lateralmost Point On The Left Hip During Backward and Forward Walking (see Table VI for standard deviations)

Comparison	Backward	Forward	Calculated t Value
Lateral	3.16	3.44	1.08
Medial	2.12	1.72	2.35*
Peak-to-Peak	5.28	5.17	0.33

The critical t value was $(t_{.05,16})$ 1.75

VIII. Comparison of Mean Horizontal Displacements and Mean Horizontal Velocities During Ascent and Descent of The Body Center of Mass (see Table VII for standard deviations)

Gait Direction	Parameter	Ascent	Descent	Calculated t Value
Backward	Displacement	7.04	7.40	1.01
	Velocity	111.16	116.78	1.01
Forward	Displacement	7.94	8.10	0.36
	Velocity	136.98	139.71	0.36

Horizontal displacements expressed as cm/5% division of the walking cycle
Horizontal velocities expressed as cm/sec, determined over 5% intervals of the walking cycle
The critical t value was $(t_{.05,18})$ 1.73

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